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Woods, S.W.

SNOW ACCUMULATION AND SNOWMELT IN
THINNED LODGEPOLE PINE STANDS AT THE
TENDERFOOT CREEK EXPERIMENTAL FOREST,
WEST-CENTRAL MONTANA

Final Research Report

**SNOW ACCUMULATION AND SNOWMELT IN THINNED LODGEPOLE
PINE STANDS AT THE TENDERFOOT CREEK EXPERIMENTAL
FOREST, WEST-CENTRAL MONTANA**

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Dr. Ward McCaughey
Rocky Mountain Research Station
Forestry Sciences Laboratory
Missoula MT 59812

Prepared by:

Dr. Scott W. Woods, Principal Investigator
Department of Ecosystem and Conservation Sciences
College of Forestry and Conservation
The University of Montana
Missoula MT 59812

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Introduction

Runoff from the winter snowpack in forested upland watersheds is the primary water source in much of western North America. Streamflow in the region varies depending on the amount of snow accumulation and the rate and timing of snowmelt, both of which can be altered by human activities such as forest harvest and fuel reduction and by natural disturbance due to fire, insect infestation and disease. Understanding and predicting the effects of forest management and natural disturbance on snow accumulation and melt is an important element of watershed management in western North America.

Snow accumulation in forested watersheds

Snow accumulation in forested watersheds varies with climate, elevation, topography and canopy structure characteristics (Pomeroy et al., 2002). Canopy structure is an especially important control on snow accumulation because of its effect on the interception component of the water budget and the wind speed and solar radiation flux at the snow surface (Harestad and Bunnell, 1981; Marks et al., 1998; Lundberg and Koivusalo, 2003). Tree removal during forest harvest or fuel reduction efforts may increase or decrease snow accumulation depending on the relative magnitude of gains due to the reduced canopy interception and losses due to increased wind scour and sublimation (Golding and Swanson, 1986; Stegman, 1996; Winkler et al., 2005).

In windy environments such as the high-elevation forests of the central and northern Rocky Mountains of western North America, snow accumulation varies with the size of the individual cutting units (Pomeroy et al., 2002; MacDonald and Stednick, 2003). Small (2 to 5 tree height diameter) clearcuts accumulate the most snow because the exposure to wind is minimized (Troendle and Leaf, 1980; Troendle and King, 1985; Swanson, 1988). Similarly, evenly distributed thinning over small areas results in a net increase in snow accumulation (Troendle and King, 1987). In contrast, large clearings in wind-swept areas may accumulate less snow than the surrounding forest (Troendle and Leaf, 1980). In less windy environments, opening size is less important and factors such as the amount of slash retention play a greater role in determining snow accumulation (Pomeroy et al., 1997).

Snowmelt in forested watersheds

Snowmelt rates are a function of the depth of snow accumulation and the energy inputs to the snowpack. Snow accumulation varies depending on the factors previously described and, in general, snow will take longer to melt in areas with deeper snow (Anderton et al., 2004). This means that the presence of snowdrifts can prolong the snowmelt period by several weeks compared to a more uniform snowpack distribution (Tarboton et al., 2000).

Most of the energy for snowmelt comes from net radiation – the sum of net solar and net thermal radiation. Additional energy for snowmelt comes from wind blowing across the snow surface, resulting in turbulent transfer of latent and sensible heat, from rain falling onto the snowpack and from energy emitted from the ground. Solar or shortwave radiation is made up of a range of wavelengths that include visible light as well as ultraviolet and near infrared. In forested areas, much of the solar energy is absorbed or reflected by the forest canopy so that net shortwave radiation below the canopy is considerably less than in open areas. When it hits the snow surface, a portion of solar radiation is reflected, further reducing the amount of solar radiation contributing energy for snowmelt. The ratio of reflected to incoming shortwave radiation is called the albedo. The albedo decreases over time as the snow surface becomes covered in debris such as pine needles and dirt, resulting in an increase in the net shortwave radiation input.

Thermal or longwave radiation is the energy re-emitted from vegetation, clouds and the land surface and consists of wavelengths from 3.0 μm to 50 μm . Longwave radiation re-emitted from the forest canopy, branches and stems is a major source of energy for snowmelt under a forest canopy, particularly in the winter months when low sun angles and short days limit the amount of solar radiation reaching the snowpack.

Under conditions of high humidity and high wind speed, turbulent energy transfer can significantly increase snowmelt rates. Rapid snowmelt during ‘rain on snow’ events is driven primarily by this wind-driven turbulent energy transfer rather than by the energy contributed by rainfall, which is generally not sufficient to cause significant melt. Wind speeds in forested areas are generally less than in the open, resulting in a decrease in the turbulent energy transfer component of the energy budget.

The physical factors controlling energy inputs to the snowpack in forested areas are complex and spatially variable. The result is that snowmelt in forested watersheds is also spatially variable at scales ranging from just a few meters to tens of kilometers. Understanding

and modeling this variability represents a challenge for hydrologists. The challenge is particularly great when dealing with forest stands that have been manipulated by thinning or harvest. Forest harvest and thinning operations contribute to the complexity of melt by affecting the distribution of snow and the energy inputs to the snowpack. When trees are removed, the snowpack is exposed to increased solar inputs, turbulent heat transfer, and redistribution, while thermal radiation inputs from the trees are reduced.

Snowmelt modeling provides a means of predicting the rate and magnitude of snowmelt based on meteorological measurements such as solar radiation flux, air temperature and wind speed. There are three main approaches to snowmelt modeling: the temperature index method, methods based on the energy budget of the snowpack, and hybrid methods that are based on a combination of temperature index and energy budget approaches. While snowmelt models have been widely applied in open areas, calibration for the effects of a forest canopy remains problematic.

Current concerns in forest management

Natural disturbance events such as wildfire and disease also affect snow accumulation and snowmelt through their effect on the forest canopy structure (Helvey, 1980). Fire suppression has sharply reduced the frequency of natural disturbance in forests throughout western North America, creating extensive, dense and overstocked stands (Sampson, 1997). By increasing canopy density, fire suppression may reduce snow accumulation and delay snowmelt in forested watersheds, with a consequent decline in water yield (Matheussen et al., 2000). This is a particular concern for water resource managers in drought prone areas such as the western United States and western Canada. Wildfire hazards due to increased fuel loads are an additional concern because of the risk to life and property. The widespread use of clearcutting to maintain water yields and reduce wildfire hazards is aesthetically, ecologically and politically undesirable, particularly since the treatments must be repeated periodically to maintain any increase in water yield. Alternative silvicultural prescriptions such as thinning offer a potentially more acceptable means of maintaining water yield and reducing fuel loads while also restoring forests to a more natural state by simulating natural disturbance processes. In order that forests can be managed in a holistic and ecologically sustainable manner, information is needed on the effects of thinning on both the magnitude and spatial variability of snow cover and the rate and timing of snowmelt.

However, relatively few studies have focused on the hydrologic effects of thinning treatments as compared to the wider literature on the effects of clearcutting.

Seral, fire-dependent lodgepole pine (*Pinus contorta*) communities comprise a significant component of mid-to upper-elevation forests in the central and northern Rocky Mountains, and provide wood products, wildlife habitat, livestock forage, water, recreational opportunities and aesthetic benefits (Koch, 1996). Fire suppression and climatic variability may have radically altered the structure of these forests. The United States Department of Agriculture, Forest Service, Rocky Mountain Research Station is investigating the use of alternative silvicultural prescriptions to restore the ecological structure and function of lodgepole pine forests in the northern Rockies, while also maintaining water yields and reducing fuel loads. As a part of these investigations, two silvicultural prescriptions, one leaving residual trees evenly distributed and the other leaving residual trees in groups were applied to lodgepole pine stands on the Tenderfoot Creek Experimental Forest in west-central Montana in 1999 and 2000. The objectives of the study described here were to: 1) determine the effect of the treatments on the magnitude and spatial variability of winter snow accumulation, 2) determine the effect of the treatments on the timing, rate and spatial variability of snowmelt, and 3) develop a simplified melt model to predict snowmelt in treated stands using readily available site metrics.

Study Area

The 3600 ha Tenderfoot Creek Experimental Forest (TCEF) lies in the headwaters of Tenderfoot Creek in the Little Belt Mountains of west-central Montana (Figure 1). Elevations in the experimental forest range from 1838 m to 2421 m with a mean of 2205 m. Glaciation and subsequent fluvial erosion has produced a landscape in which broad, rounded ridgelines separate steep-sided stream valleys with frequent rock outcrops and talus slopes. Lodgepole pine is the dominant tree species in each of the four subalpine fir habitat types found at TCEF (Farnes et al., 1995). Other species include subalpine fir, Engelmann spruce, whitebark pine (*Pinus albicaulis*), Douglas-fir (*Pseudotsuga menziesii*), and quaking aspen (*Populus tremuloides*). Tree height averages 15 m, and leaf area index (LAI) values range from 2.8 to 3.2.

The elevation weighted mean annual precipitation at TCEF is 88.4 cm (Farnes et al., 1995). Precipitation is evenly distributed throughout the year, but between October and April most of the precipitation accumulates as snow. The mean peak snow water equivalents (SWE_{max})

at the Stringer Creek and Onion Park SNOTEL sites (elevations 1997 m and 2258 m), both located within TCEF, are 28.2 cm and 37.6 cm, respectively (Figure 1). On average, snowfall comprises 40% and 47% of the annual precipitation at Stringer Creek and Onion Park respectively. Peak runoff in Tenderfoot Creek typically occurs between mid-May and early June, and is associated with snowmelt and spring rainfall. The mean annual runoff from the upper part of the Tenderfoot Creek watershed is approximately 30.0 cm. Winds are typically out of the west. Mean daily temperatures at the Onion Park SNOTEL site range from minus 8.4 °C in December to 12.8 °C in July.

Methods

Silvicultural Treatments

Two silvicultural treatments were installed in 1999 and 2000 in the 346 ha Sun Creek subwatershed of Tenderfoot Creek (Figure 1). The treatments were shelterwood-with-reserve prescriptions with ~50% basal area removal, and followed procedures for structural retention harvest outlined by Forest Ecosystem Management Assessment Team (1993) and Franklin et al., (1997). In the first treatment (SE), the residual trees were evenly distributed, and in the second (SG) the residual trees were in 0.2 to 0.8 ha groups with intervening corridors where all of the trees were removed (Figures 2 and 3). Ground-based felling and yarding methods were used for both treatments. The treatment units were located on both east and west aspects and at elevations ranging from 2168 to 2261 m (Table 1 and Figure 1). The SE treatment replicated the effect of a low-intensity mixed-severity wildfire, where many of the mature trees survived the fire. The SG treatment emulated the effect of stand-replacing wildfire where all trees were killed in swaths or corridors while groups remained largely unburned. The long-term goal of both treatments is to create two-aged stand structures that are robust to disturbance events such as wildfire, disease and insect infestation (Forest Ecosystem Management Assessment Team, 1993).

Snow Accumulation

Field measurements of the snowpack were obtained in mid-April 2003, late March 2004 and mid-March 2005. The measurement periods were scheduled to coincide with the peak of the snowpack accumulation in the study area. Measurements were conducted in the SE and SG

treatments and a comparable 13 ha control area on the eastern side of the Sun Creek watershed (Figure 1). Sampling locations were selected by delineating a systematic 55 m orthogonal grid of points within each of the treatments and the control using ArcGIS. A 30 m (~2 tree height) buffer was defined around the perimeter of each thinned stand and the control stand to reduce edge effects. The number of sampling points ranged from 270 in 2003 to 286 in 2004 because of modifications to the sampling grid between years. Sample locations were identified in the field using a Geographic Positioning System (GPS) and a tape and compass, and then marked using plastic wands. In the group retention plots, the position of each sampling point relative to the edge of a group was defined as either inside (SG-I), outside (SG-O), or within 5 m of the edge of a group (SG-IE or SG-OE) to facilitate spatial analysis of snow accumulation patterns. At each location, the snow depth and snow water equivalent (SWE) were measured at three points within 2 m of the marker wand using a Federal snow sampler, and the mean of the three values was recorded.

Field observations in 2003 and 2004 indicated that the snowpack depth and snow water equivalent varied within the SG treatment depending on the location relative to the edge of the retention groups. To investigate the effect of position within the treatment, snow depth measurements were collected at 5 meter intervals along north-south and east-west transects extending across nineteen of the retention groups in 2005. Transects started in openings between groups and extended through the center of a group and into the opening on the other side.

Ancillary data

Data from the Onion Park SNOTEL site, which is located within TCEF at a similar elevation to the treatment and control units, was used to compare the winter snowpack characteristics in 2003, 2004 and 2005 to the long-term average. Canopy density at each of the snow accumulation survey and snowmelt lysimeter locations was determined from hemispherical photographs taken with a Fuji Finepix digital camera equipped with a fisheye lens. All photos were processed using the Gap Light Analyzer (GLA) software package (Frazer et al., 1999). Effective Leaf Area Index (ELAI) and the percent open canopy were obtained from the photographs. Elevation, aspect, latitude, longitude, and slope were recorded at each site. A geographical positioning system was used to collect the elevation and spatial coordinates of each site. A clinometer and a compass were used to measure slope and aspect, respectively.

Data Analysis

Analysis of variance (ANOVA) was used to test for differences in the snow depth and snow water equivalent values between the two treatments and the control within and between years. Linear contrasts were used to determine which treatments were significantly different, and the Bonferroni adjustment was used to control the experiment-wise error rate at an alpha level of 0.05 (Dunn, 1961).

Predictive models for snow accumulation in the SE treatment and the control were developed by applying a canopy interception function to the observed snow accumulation in the open at the Onion Park SNOTEL site during each storm. Canopy interception rates in conifer forests may be constant (McNay et al., 1988) but more commonly they decrease at varying rates with increasing snowfall (Harestad and Bunnell, 1981; Calder, 1990; Hedstrom and Pomeroy, 1998; Pomeroy et al., 1998). Both constant canopy interception rates and rates that declined as both inverse linear and inverse exponential functions of total storm snowfall and mean storm intensity (cm SWE day^{-1}) were evaluated. A storm was defined as a period of one or more consecutive days when snowfall was recorded at the Onion Park SNOTEL site, and storm intensity was the mean of the daily snow water equivalent totals during the storm.

The model-predicted snowfall totals in the control and the SE treatment for each storm were summed over the period prior to sampling in 2003, 2004 and 2005 and compared to the observed mean snow water equivalents. Model fit was evaluated using the average percent deviation statistic (Martinec and Rango, 1989).

A least squares stepwise multiple regression procedure was used to develop a predictive model for the 3-year mean SWE at each site in the treatments and the control. The independent variables in the model were the percent open canopy, the effective leaf area index, slope, aspect, elevation and surface roughness. Pearson and Spearman rank correlation matrices were used prior to regression modelling to test for multicollinearity among the independent variables. If two independent variables were correlated, the variable that had the lowest linear relationship with SWE was removed from the analysis.

Snowmelt

Twelve snowmelt lysimeters were installed in TCEF in 2004 and 2005 to investigate the effects of the treatments on the rate and timing of snowmelt. The lysimeter locations were chosen to capture the various elevations, aspects, and canopy coverage within the two treatments and the control (Figure 4). Three lysimeters were placed in the control unit, three in the SE treatment, and six in the SG treatment. The lysimeters in the control unit were placed at least 50 m from any natural or man-made openings to reduce edge effects. In the SG treatments the lysimeters were paired, with one lysimeter inside a retention group and the other located at the same elevation and aspect in an adjacent opening.

Each lysimeter was a 1 m x 1 m steel pan with a 10 cm high rim welded around the outside and a drain near the front center. A grid of expanded steel was placed in the bottom of the lysimeter and a screen was placed over the drain hole to reduce the possibility that needles, branches and other debris would block the drain. Snowmelt percolating into the pan was routed to a tipping bucket mounted in a cooler buried beneath the ground surface in front of the pan. Each tip of the tipping bucket mechanism indicated approximately 0.3 mm of melt ($\sim 300 \text{ cm}^3$ of melt water). A Hobo® Event Logger recorded the date and time of each tip. Data from the event loggers was downloaded twice each year, at the time of the snow accumulation survey and after snowmelt was complete. The tipping bucket mechanisms were calibrated prior to deployment in the field, in October of each year and after the final snowmelt season in July 2005. Field calibrations were performed by allowing approximately 40 L of water, equivalent to 40 mm of melt, to run into the lysimeter over a 2 to 3 hr time period.

Ancillary Data

An automated weather station was installed in the SE treatment during the winters of 2004 and 2005. Upward and downward facing CM3 pyranometers measured the incoming and reflected solar radiation, and a NR-Lite net radiometer measured the net radiation. Wind speed, air temperature and relative humidity were measured using Campbell Scientific electronic sensors. Output from the sensors was recorded each hour by a Campbell Scientific CR10-X data logger equipped with a solar panel power source. In 2005, I-Button temperature sensors were installed at each of the lysimeters, one at ground level and one two meters above the ground. These sensors recorded temperature values every hour throughout the melt period.

Snowmelt Modeling

Three types of model were used to predict snowmelt in TCEF; a temperature index model, a hybrid model, and an energy balance model. Each model was first calibrated to daily snowmelt data from the Onion Park SNOTEL station. The calibrated models were then used to predict the melt at the lysimeters. Model fit was evaluated using the Nash – Sutcliffe efficiency coefficient R_{NS}^2 (Nash and Sutcliffe, 1970):

$$R_{NS}^2 = 1 - \frac{\sum_{i=1}^N (Q_i - \hat{Q}_i)^2}{\sum_{i=1}^N (Q_i - m_Q)^2} \quad (1)$$

where Q_i is the i^{th} observed value, $\hat{Q}_i$ is the i^{th} predicted value, m_Q is the mean of the observed values and $i=1,2,3$ etc. Values for R_{NS}^2 between 0 and 1 indicate that the modeled values provide a better estimate than a simple average of the observed values.

Temperature index method

The basic form of the temperature index model (Martinec, 1989; Davies, 1997; Rango and Martinec, 1995; Hock, 2003) is:

$$M_f = C_f (T_{ave} - T_b) \quad (2)$$

where M_f is the depth of daily melt (cm), and C_f is the coefficient of melt ($cm \text{ } ^\circ C^{-1}$), T_{ave} is the average daily temperature ($^\circ C$), and T_b is the base temperature, which is usually taken to be $0^\circ C$. Correctly estimating C_f is critical for accurate prediction of the melt rate using the temperature index method. In this study separate values for C_f were calculated for April, May and June using historical snowmelt and temperature data from the Onion Park SNOTEL site. For each year in the period of record all the positive values for daily average temperature during a month were summed and plotted against the total melt for the month. The total melt was calculated as the overall decrease in SWE plus the daily rainfall over the period. The melt coefficient for each month was the slope of the linear regression of total melt versus the summed positive daily temperature values.

Hybrid method

Brubaker et. al. (1996) and Kustas and Rango (1994) proposed the following hybrid model for predicting snowmelt:

$$M = a_r T_{ave} + m_Q Rn \quad (3)$$

where M is melt ($cm\ d^{-1}$), a_r is a restrictive degree-day factor, m_Q is a conversion factor for energy flux density to snowmelt depth ($cm\ d^{-1} (Wm^{-2})^{-1}$), and Rn is the net radiation (Wm^{-2}). By incorporating the net radiation, the hybrid model should provide a better estimate of melt than the temperature index method, without the complexity involved in using the energy balance approach. Daily site-specific values for a_r can be calculated using wind speed, humidity, and temperature or the model can be calibrated using a single value to represent the entire snowmelt period. In this study both seasonal and daily a_r values were used and their ability to accurately predict melt was compared. Climate data for the hybrid equation was obtained from the weather station installed in the SE treatments.

Energy budget method

The general form of the energy budget equation is:

$$S = (k + L) + H \pm (LE) + R + G \quad (4)$$

where S is the energy available to melt snow, $(k+L)$ is the net radiation, H is the turbulent exchange of sensible heat, (LE) is the exchange of latent heat, R is the energy input from rainfall, and G is the energy input from the ground. The melt rate (ΔW) is calculated from:

$$\Delta W = \frac{S}{\rho_w \cdot \lambda_f} \quad (5)$$

where ρ_w is the density of water, and λ_f is the latent heat of fusion. The energy budget model is the most data intensive method for calculating melt, but it is also usually assumed to be the most

accurate because it directly quantifies the physical, energy-based processes that result in snowmelt. All the climate data used to calculate the melt rate were obtained from the weather station located in the treatment units.

Modeling of canopy effects

To adjust the hybrid and energy budget models for canopy effects, radiation under the canopy was calculated in accordance with USACE (1956). Longwave and shortwave data was collected in the openings for melt years 2004 and 2005. Net longwave radiation under the canopy (L_{NC}) was calculated from:

$$L_{NC} = F \times (\sigma T^4 - (\sigma T^4 - 2.5)) + (1 - F) \times L_{open} \quad (6)$$

where F is a measure of forest canopy, σ is the Stefan-Boltzmann constant, and L_{open} is the net longwave radiation in the open. Net shortwave radiation under the canopy (K_{NC}) was calculated from:

$$K_{NC} = K_{open} \times \exp^{(-3.91 \times F)} \quad (7)$$

where K_{open} is the shortwave radiation measured in the opening and F is a measure of forest cover. Net radiation under the canopy Rn_{can} was calculated from:

$$Rn_{can} = K_{NC} + L_{NC} \quad (8)$$

The calculated values for net radiation under the canopy were used in the hybrid and energy balance models to calculate snowmelt at the lysimeter situated under the forest canopy.

Results

Snow accumulation and melt at the Onion Park SNOTEL site

Snow accumulation at TCEF was close to average during the three-year study period. The

peak snow water equivalent (SWE_{max}) at the Onion Park SNOTEL site was within 1.5 cm of the mean of 37.6 cm in all three years (Figure 5), and averaged 84% of the total snowfall. Sampling of the snowpack in 2003 took place almost a month before the peak snowpack, but the SWE at Onion Park was less than 3 cm below the SWE_{max} of 36.8 cm (Figure 5). In 2004, the snowpack sampling was conducted 9 days after the peak, when the SWE at Onion Park had decreased 1.3 cm from the SWE_{max} of 36.1 cm. In 2005, the snowpack sampling was conducted approximately one month prior to the peak snow accumulation at the Onion Park site, and there was considerable late season snowfall. Consequently, the SWE during the 3-day sampling period (18-20 March 2005) was 9.4 cm less than the SWE_{max} of 38.6 cm.

Snow accumulation in treatments and control

Differences among the treatments and control plots, within and between years, followed similar patterns for both SWE and snow depth. The highest snow accumulation values in the treatment and control plots were measured in 2004, when the mean snow water equivalent (SWE_{mean}) values were 22 to 37% higher than in 2003 and 52 to 67% higher than in 2005 (Table 2). Although both 2003 and 2004 had similar snow accumulation at Onion Park, there was almost 8 cm more snow water equivalent in the control plot in 2004, which had a similar number of storms to 2003 but more days with heavy snowfall.

There was no significant difference in SWE between the east and west aspects of either treatment in any year. Therefore, data from the east and west aspects were combined for analysis. Differences in snow accumulation between the control and the Onion Park SNOTEL site indicated seasonal interception rates of between 20% and 40% for the intact canopy (Table 2). In all three years, the highest mean snow water equivalent (SWE_{mean}) was in the SE treatment, where the values were 7.2, 5.6 and 1.7 cm higher than the control in 2003, 2004 and 2005, respectively (Figure 6 and Table 2). The difference in SWE_{mean} between the SE treatment and the control was statistically significant in both 2003 and 2004 ($P < 0.0001$), but not in 2005. The SWE_{mean} in the SE treatment was significantly greater than the SG treatment in all three years ($P < 0.0001$). In contrast, the SG treatment mean was within 1.0 cm of the control value in all three years, and none of the differences in SWE_{mean} between the SG treatment and the control was significant.

The variability of the SWE measurements in the SE treatment, as indicated by the coefficient of variation (CV), was similar each year, and was slightly lower than in the control (Table 2). In contrast, the SG treatment had SWE values that were 1.5 to 2 times more variable than the control and up to 3 times more variable than in the SE treatment. Part of this variability was due to a strong contrast in snow accumulation between sampling locations inside a group (SG-I) compared to those in the openings between groups (SG-O). The SWE_{mean} in the SG-I sites was 26%, 25% and 35% less than in the SG-O sites in 2003, 2004 and 2005, respectively, and all of the differences were significant ($P < 0.006$) (Figure 4). The SG-I SWE_{mean} was also significantly less than that in the control in all three years, and the SG-O sites had a SWE_{mean} that was significantly less than in the SE treatment. Sites within 5 m of the edge of a group (SG-IE and SG-OE) had mean SWE values that were intermediate between those for the SG-I and SG-O locations (Figure 7).

The data from the snow depth transects conducted in the SG treatment in 2005 also showed a strong contrast between snow depths in the groups and in the openings (Figure 8). The mean snow depth for transect locations in the openings (109 cm) was significantly greater than that for locations in the groups (73 cm).

Snow accumulation within the SG treatment varied with distance from the edge of a group, both inside the groups and in the openings, and this resulted in even greater overall spatial variability. The snow depths measured along the transects within the groups decreased with distance between the north and south facing edges, so that snow depth on the southern edge of groups was less than half that measured on the northern edge (Figure 8). Similarly, the mean snow depth in the openings within 30 m of the south side of groups (108 cm) was significantly less than that in the openings within 30 m of the north side of a group (116 cm) ($P < 0.0001$). There were no comparable trends in snow depth, either in the groups or in the openings, along the west to east transects.

Interception models

The best models for predicting the cumulative snow accumulation prior to sampling in each year were obtained when the interception rates in the control (I_{con} , %) and SE treatment (I_{SE} , %) were calculated as inverse exponential functions of mean storm intensity (S , cm SWE day⁻¹):

$$I_{\text{con}} = 13.46 + 158 e^{(-3.5S)} \quad (9)$$

$$I_{\text{SE}} = 10.25 + 120 e^{(-3.5S)} \quad (10)$$

Equation 9 predicts that the interception rate in the control stand decreases from more than 70% for mean storm intensities of less than 0.3 cm SWE day⁻¹ to less than 20% for storm intensities of more than 1.0 cm SWE day⁻¹. Equation 10 predicts that the storm interception rate in the SE treatment is less than in the control, ranging from over 60% for storm intensities of less than 0.25 cm SWE day⁻¹ to less than 15% for storm intensities greater than 1.0 cm SWE day⁻¹. When these interception functions were used to predict seasonal snow accumulation totals in the control and the SE treatment, the average percent deviation values for the 3-year study period were 9.4% and 7.5%, respectively (Table 3).

Regression analysis

The only significant variable in the stepwise multiple regression analysis of the influence of site factors on the mean SWE at a site was the percent open canopy (CAN):

$$\text{SWE} = 11.6 + (0.16 \cdot \text{CAN}) \quad (11)$$

This regression model is statistically significant ($F = 215.1$, $P < 0.0001$), and explains 51% of the variability in SWE among sites in both of the treatments and the control. Effective leaf area index (LAI_{eff}) was dropped from the regression because it was significantly correlated with the percent open canopy ($P < 0.0001$, $r^2 = 0.98$). There was no relationship between the mean SWE and slope, aspect, elevation or surface roughness.

Snowmelt in treatments

In 2004, seven of the twelve lysimeters functioned properly, two in the control, one in the SE treatment, and four in the SG treatment. Two of the functional lysimeters in the SG treatment were inside the groups and two were in opening between groups. In 2005, seven of the twelve lysimeters collected data: two in the SE treatment and five in the SG treatment. However, all of the lysimeters were seriously affected by clogging and freezing in 2005, so that only the 2004 data were used for assessing the effectiveness of the various melt models.

Snowmelt at most of the lysimeters started on April 9th and ended on June 10th 2004 (Table 6), later than at the nearby Onion Park SNOTEL site where snowmelt started on March 19th and ended on June 4th. Surprisingly, there was no difference in the timing of melt between sites in the open and in the retention groups in the SG treatment or in the control. The lysimeter at site 152 stopped recording melt on May 8th but this was likely because of an equipment failure rather than the actual end of melt as the other lysimeter in the control continued recording melt for almost another month.

The overall pattern of melt in the lysimeters was consistent with the observed temperature fluctuations during the melt period (Figure 9). For example from April 30th to May 8th the average daily temperatures was 8°C and melt was more rapid. On May 10th the temperature dipped to near 0°C and the melt rate declined substantially. The average daily melt rates in the SG treatment (0.76 cm day⁻¹) and the control (0.78 cm day⁻¹) were very similar. However the maximum daily melt rate at lysimeter 80, located in an opening within the SG treatment, (4.4 cm day⁻¹) was almost double that in the control (2.6 cm day⁻¹). The total melt at the SG-I sites was within 3% of that in the control, whereas the total melt at the SG-O sites was 16 to 37% higher than at either the SG-I or the control, reflecting higher peak snow accumulation in open areas (Figure 9).

Melt rates at sites within the control were within 14% of each other throughout the melt period. In one of the lysimeter pairs in the SG treatment lysimeter 80, located in the open, recorded a consistently higher daily melt rate than lysimeter 65, situated in the interior of a retention group (Figure 10). For example on May 4th lysimeter 80 recorded 4.4 cm of melt while lysimeter 65 recorded just 2.3 cm. This contrast in melt rates was not observed in the other set of paired lysimeters, 148 and 132 (Figure 10). This is likely due to the fact that the “interior” lysimeter in this pair, lysimeter 132 lies within 5 m of the south edge of the group where it presumably receives more solar radiation.

There was not enough data from the SE treatment to allow a comparison to be made with the SG treatment or the control. From the limited data that were collected from lysimeter 239 in the SE unit, the peak melt rate was higher than in the control and more comparable to the group unit lysimeters.

Snowmelt modeling at Onion Park

Temperature index model

The melt coefficients calculated from the historical data from Onion Park were 0.165, 0.179, and 0.285 cm day⁻¹ °C⁻¹ for April, May and June, respectively. However, rather than using different melt coefficients for each month, the coefficient corresponding to the month in which the majority of melt occurred was used. In 2004, most of the melt occurred between late April and late May, so the May coefficient of melt was used in the temperature index model. In 2005, most of the melt occurred between late May and early June, so the June coefficient of melt was used to predict melt rates.

In 2004, the temperature index (*TI*) model provided a reasonably good fit to the observed melt at the Onion Park SNOTEL site. Although, the model over estimated the daily melt rate towards the end of the melt period, the Nash Sutcliffe R^2 was still fairly high at 0.67 (Table 5 and Figure 11). The model performed less well in 2005 when it consistently over estimated daily melt throughout the melt period and the Nash Sutcliffe R^2 was just 0.43 (Figure 11). The model performed better when predicting the cumulative melt during the melt period than it did for individual daily values. The cumulative melt totals predicted by the *TI* model were within 17 and 6% of the melt recorded during the snowmelt period at the Onion Park SNOTEL site in 2004 and 2005 respectively (Figure 12).

Hybrid temperature index method

The hybrid temperature index model was used with both seasonal (constant) and daily calculated values for the coefficient of melt. Published values for the coefficient of melt range from 0.20 to 0.25 cm °C⁻¹ day⁻¹ (Martinec, 1989), however Brubaker et. al. (1996), found that values could be lower if wind and humidity are low. Surprisingly, both hybrid models were poor predictors of daily melt, and performed more poorly than the basic TI model (Figure 13). In 2004 the hybrid model using a coefficient of melt from within the range of calculated values ($HTIM_{sv}$) had a R_{NS}^2 value of 0.10. When daily calculated coefficient of melt values were used in the model ($HTIM_{dv}$) the R_{NS}^2 increased to 0.25 (Table 5). The results were similar for the 2005 data; the R_{NS}^2 values for the $HTIM_{sv}$ and $HTIM_{dv}$ models were 0.23 and 0.29, respectively (Table 5).

In 2004, the $HTIM_{sv}$ and $HTIM_{dv}$ models over estimated the observed cumulative melt at the end of the melt season by 22% and 18% respectively. In 2005, the models substantially over predicted melt after mid-May so that by the end of the melt period the $HTIM_{sv}$ over predicted cumulative melt by 27% and the $HTIM_{dv}$ over predicted melt by 29% (Figure 14).

Energy Balance Model

The energy balance (EB) modeling results were similar to those obtained using the $HTIM_{dv}$ hybrid model (Figure 15). In 2004 the EB model fit resulted in a R^2_{NS} of 0.10 for daily melt values, and in 2005 the R^2_{NS} was 0.25 (Table 5). Similarly to the hybrid model, the EB model over predicted melt by 19% by the end of melt in 2004 (Figure 16). In 2005 the EB model over predicted melt by 29% (Figure 16).

Modeling snowmelt in the treatments

Modeling of snowmelt at the lysimeters was conducted using the hybrid model with a seasonal value for the coefficient of melt. When this model was used to predict snowmelt in the two lysimeters in the open (148 and 80), the results were similar to those obtained at the Onion Park SNOTEL site. A coefficient of melt of 0.15 fit provided the best fit to the observed values, and resulted in R^2_{NS} values of 0.29 and 0.43 for lysimeters 148 and 80, respectively (Table 6). The best fit between the observed and predicted values was obtained in the early part of the melt season (Figure 17). By the end of the melt season cumulative melt was over predicted by 21 and 31% at lysimeters 148 and 80 respectively (Figure 18).

The unadjusted hybrid model over predicted daily melt at sites under the canopy at all locations regardless of canopy coverage (Figure 19). Canopy measurements indicated that sites 65 and 132 in the retention groups had canopy coverage values of 0.68 and 0.63 respectively. The canopy cover values at sites 52 and 152 in the control were 0.74 and 0.64 respectively. Adjusting the hybrid model for the presence of forest canopy substantially improved the model fit in all but one of these lysimeters by reducing the net radiation available for melt, so reducing the overall melt rate. The exception was lysimeter 132, where the best model fit was obtained by assuming zero canopy cover (Figure 19). Lysimeter 132 is located 15 m from the edge of the

group with a southwest facing aspect. It is likely that this lysimeter receives larger inputs of energy than would occur if the canopy was continuous throughout the stand.

The adjusted hybrid model was a good predictor of cumulative melt at all of the lysimeter sites beneath the canopy except 132. The total cumulative melt recorded at lysimeter 65 was over predicted by 61% with the unadjusted model and only a 7% over prediction with the adjusted model. The unadjusted model under predicted cumulative melt by 2% at lysimeter 52 and was nearly perfect with the adjusted model. Cumulative melt was over predicted by 42% at lysimeter 152 with the unadjusted model and under predicted cumulative melt by 24% with the adjusted model, and at site 132 the adjusted hybrid model over predicted the cumulative melt by 50%, whereas the unadjusted model under predicted by 22% (figure 20).

Discussion

Effects of Thinning on Snow Accumulation

Previous research on the hydrologic effects of forest management has shown that the effect of complete tree removal on snow accumulation depends on the spatial arrangement and size of the cutting units (Golding and Swanson, 1978; Troendle and Leaf, 1980; Troendle and King, 1985). Similarly, the results of the present study demonstrate that the effect of partial tree removal (thinning) on snow accumulation depends on the spatial arrangement of the residual trees within the treatments. Both of the thinning treatments used in this study involved the removal of approximately 50% of the stand basal area. However, in the even distribution treatment, tree removal was conducted evenly across the stand, leaving trees spaced 5 to 10 m apart. In the group retention treatment, the silvicultural prescription involved the removal of all the trees in some areas with 0.2 to 0.8 ha groups of trees left intact elsewhere. The SE treatment resulted in an increase of up to 35% in the mean snow water equivalent relative to the control, while the SG treatment had no significant effect on the magnitude of snow accumulation when measured at the stand scale. We attribute this to differences in the way that the spatial arrangement and size of the groups affected canopy interception, sublimation and wind scour.

Precipitation and canopy interception are the primary controls on snow accumulation in forested watersheds. Consequently, snow water equivalent during the accumulation phase is inversely proportional to the canopy density (Harestad and Bunnell, 1981; Gary and Troendle,

1982; Moore and McCaughey, 1997; Winkler, 2001; Teti, 2003) and partial removal of the canopy by evenly spaced thinning generally results in an increase in SWE (Haupt, 1979; Gary and Watkins, 1985; Troendle and King, 1987). The increase in SWE in the SE treatment relative to the control, which averaged 4.8 cm (21%) over the three years, is identical in magnitude and similar in proportion to the 4.8 cm (16%) increase in SWE observed following a 41 ha shelterwood cut in Colorado that reduced the basal area by 40% (Troendle and King, 1987). The increase is also similar to that reported from a very dense lodgepole pine stand in Wyoming, where the mean SWE increased by 5.3 cm (30%) after thinning (Gary and Watkins, 1985). In both of these studies the increase in SWE was attributed primarily to reduced interception, and a similar conclusion is appropriate for the present study.

The interception functions used to calculate storm-by-storm snow accumulation in the control and the SE treatment (equations 9 and 10) resulted in a reasonably good fit between the observed and predicted values for the corresponding seasonal snow accumulation totals. The inverse relationship between the interception rate and average storm intensity contained in these models is generally consistent with other snow interception studies (e.g. Strobel, 1978; Harestad and Bunnell, 1981; Calder, 1990; Hedstrom and Pomeroy, 1998). The low interception efficiency for storm intensities of greater than 0.5 cm SWE day⁻¹ can be attributed to the sparse canopy cover and widely spaced branches in the high-elevation lodgepole pine forest present in the study area.

Interannual differences in snow accumulation in the control and the SE treatment can be explained in terms of the interception models and differences between years in the storm characteristics. The snow accumulation totals at Onion Park in 2003 and 2004 differed by less than 1 cm, but in 2004 there was 7.6 cm more SWE in the control and an additional 6.0 cm in the SE treatment. The higher snow accumulation below the canopy in 2004 was because more of the snow was delivered on days with high snowfall, when interception captured proportionally less of the total: there were 18 days in 2004 when the snowfall exceeded 0.5 cm SWE compared to just 15 days in 2003. Based on the interception models (equations 9 and 10) the three highest daily snowfall totals in 2004 accounted for an additional 6.0 cm of SWE in the SE treatment and the control, respectively. Thus, snow accumulation under a forest canopy can vary considerably between years with similar gross precipitation depending on the distribution of daily snowfall totals.

In 2005, there was less snowfall overall than in 2003 or 2004, and this was the primary reason for the reduced snow accumulation in the treatments and the control. There was also a greater relative difference in snow accumulation in the SE treatment and the control compared to Onion Park, and this was due to a reduced number of days with heavy snowfall. There were just 11 days when the snowfall exceeded 0.5 cm SWE, so that the overall canopy interception in both the SE treatment and the control was proportionally higher than in 2003 or 2004.

The interception functions developed for this study may be used to predict snowfall under the canopy in similar forested areas elsewhere in the northern Rocky Mountains. However, like all empirically based models in snow hydrology, the models may not perform well when the climatic and land surface conditions are different from those on which the model is based. The study encompassed three years with similar snowfall totals that were very close to the long term average, so the best model performance would be expected under similarly “average” conditions.

The absence of a significant treatment effect in the SG treatment was due to increased sublimation losses from the retention groups and in the openings between groups, which offset gains due to decreased interception in the openings. Evidence for increased sublimation from the retention groups comes from the fact that the mean SWE inside the groups (SG-I) was less than in the control, despite the similarity in canopy density. Snow depth decreased along the north to south transects within the groups, indicating that increased sublimation of snow in the canopy was largely due to increased exposure to solar radiation, with the greatest effect occurring on the more exposed south side of the groups. Snowpack temperature and snowmelt data collected for a related study indicates that mid-winter melt generally does not occur in the treated stands, so the observed losses can only be due to sublimation (Sappington, 2006).

Sublimation losses from the retention groups may have been enhanced by higher wind speeds within the canopy. Snow blown from a forest canopy is subject to increased sublimation because of the increased exposure and ventilation of the snow crystals (Pomeroy et al., 1998). The retention groups are all less than 0.8 ha, so that the maximum distance from the edge of a group to the center is about five times the average tree height. Increased wind speeds have been measured at distances of up to five times the dominant tree height from forest edges in fragmented forest landscapes (Chen et al., 1995).

In 2003 and 2004 the mean SWE in the openings in the SG treatment (SG-O) was less than in the SE treatment, despite the absence of canopy interception, suggesting that sublimation

losses also occurred in the openings between groups. As in the retention groups, blowing snow may have increased the sublimation rate. There were signs of wind scour in the openings, such as bare areas on the windward side of ridge crests and wind-formed ripples on the snow surface, particularly in openings oriented parallel to the prevailing westerly wind. However there was no evidence that this snow was being re-deposited elsewhere in the treatments.

The removal of slash from the openings when the treatments were installed may have increased the losses due to blowing snow. Slash and surface vegetation help to retain snow in logged openings, while the removal of these surface roughness elements generally results in increased blowing snow sublimation and wind scour (Pomeroy et al., 1997). Regrowth of surface vegetation within our treatment plots may have increased the surface roughness, resulting in an increase in snow retention. This could explain why, in contrast with the two previous years, the mean SWE in the openings in 2005 was greater than in the SE treatment. Annual snow accumulation measurements in the treatments and the control are continuing, and these data will be used to distinguish the effects of vegetation regrowth from interannual differences in climate.

Three critical assumptions were made in our interpretation of the study results. First, we assumed that spatial differences in canopy interception were insignificant prior to treatment. Since the treatment watershed has never been logged, the main influence on canopy density and hence on canopy interception is natural disturbance by fire. Fire history data for the Tenderfoot Creek Experimental Forest indicate that most of the treatment and control units last burned 130 years ago, although about 30% of the SG treatment is in a stand that burned 239 years ago (Barrett, 1993). Moore and McCaughey (1997) reported only a 1 to 2 cm difference in April SWE between a 123-year-old and a 270-year-old lodgepole pine stand at TCEF, suggesting that pre-treatment differences in canopy interception in our study site were minimal.

The second assumption was that SWE losses due to snowmelt prior to the measurement period did not affect the outcome of the study. Differences in snow accumulation between forest harvest treatments may be confounded by differential snowmelt rates prior to measurement (Lundberg and Koivusalo, 2003). Melting generally occurs earlier and more rapidly in open areas compared to sites under a closed canopy (Pomeroy and Granger, 1997). The only years potentially affected by snowmelt prior to the measurements were 2003 and 2004, which had 1.3 cm of melt at Onion Park prior to the start of sampling. Differences between the treatments and the control in these two years may have been partly due to differential snowmelt. However, more

rapid melt in the SE treatment would tend to decrease rather than increase the difference in SWE relative to the control. In the SG treatment, melt rates may have been higher than at the Onion Park SNOTEL site due to the presence of significant edge effects. However, even with an additional 1 to 2 cm of SWE in this treatment there would still have been a significant difference between the SE and SG treatments in 2003 and 2004.

The last assumption was that differences between treatments due to topography were minimal. Snow accumulation patterns in mountainous areas can be significantly altered by redistribution due to the interaction between wind and topography (e.g. Winstral et al. 2002). However, the similar elevation and aspect distributions of the treatments and the absence of prominent ridgelines or depressions, which accumulate less and more snow than flat areas, respectively (Lundberg and Koivusalo, 2003) suggests that topographic effects are likely to be less important here than in other areas.

Effect of canopy cover on snowmelt

The forest canopy exerts a strong control over the energy available to melt snow (Gary and Troendle, 1982). In this study, canopy cover was important in controlling the maximum daily melt rates in the treatments. The SG treatment included areas with a full canopy within the retention groups and areas with no canopy cover in the surrounding openings. The daily maximum melt rates were up 40% higher in the openings compared to the control. These accelerated melt rates may be due to the larger inputs of solar radiation because of a lack of attenuation by the forest cover or warm winds that are common to the forests east of the continental divide in central Montana. In contrast, the maximum melt rates inside the retention groups were not statistically different with the exception of lysimeter 132. Lysimeter 132 is located within 5 meters of the edge of a group, so it may have been exposed to radiation levels more comparable to the SG-O sites. A second possible source of additional radiation is from longwave radiation emitted from tree warmed by the sun due to the proximity to the edge of the group.

The results show that the SG treatment increased the variability in the maximum daily melt rate compared to an uncut control. From the limited data available, it appears that the daily maximum melt rates in the evenly thinned unit were similar to the maximum melt rates in the

open in the SG treatment. This makes sense because the percent open canopy at site 239 was 0.93, which is similar to the values measured at the SG-O sites.

Surprisingly, the presence of canopy cover had little to no effect on the timing and duration of snowmelt. This may be due to the limitations associated with measuring snowmelt using small lysimeters (Kattelmann, 2000). In some cases, the lysimeter drains collected debris, creating a place for ice to form and clog the drains. This clogging probably led to false recording of the timing of melt particularly early in the melt season. In some cases, the rapid outflow of melt water following the unclogging of the drain may have led to artificially high maximum daily melt rates.

Snowmelt modeling at Onion Park

Energy budget and hybrid models that include a radiation component are generally more accurate at predicting melt on a daily basis than temperature index (TI) models. However, at the Onion Park site, the temperature index model performed better than either the hybrid model or the energy balance model. The location of the Onion Park SNOTEL makes it well suited for modeling using a TI methodology for two reasons. First, the Onion Park station lies in a small clearing, where the majority of the radiation warming the snow pack is direct solar radiation rather than long wave radiation. Second, wind effects are minimal inside the small clearing where the Onion Park SNOTEL station is located, so that turbulent transfers of energy to the snowpack are much reduced. Under these circumstances, where solar radiation is the most important energy source, the air temperature is a good measure of the amount of energy available for melt and the TI approach works well. The model would not perform as well in a more cloudy, foggy or windy environment, and would have little value for predicting melt under a forest canopy due to the dominance of long wave radiation sources.

The fact that both the hybrid and energy balance models performed badly suggests that the poor model performance was caused by problems with the radiation data used to calculate snowmelt. In both 2004 and 2005, the hybrid and energy balance models consistently over-predicted melt towards the end of the melt season, and this was the primary cause of the low NS coefficients obtained for these models. This suggests that the radiation flux values used to calculate the melt rate were too high. Radiation data for the models was obtained from sensors at the climate station located within the SE treatment in a relatively flat and open area. In contrast,

the Onion Park site lies in a small clearing where trees cast a shadow across the snow surface for much of the day. The over-prediction of melt in the latter half of the melt season could be because the climate station, located in an open area, received more solar radiation on a daily basis than the Onion Park snow pillow. The implication is that small variations in the radiation flux due to the presence of shadows at the edges of stands and in clearings can significantly affect the ability of energy based models to predict snowmelt at a point. Since treated stands have unusually high number of “edges”, snowmelt modeling is even more difficult than in untreated stands with a more continuous canopy.

Use of the hybrid model requires the selection of an appropriate value for the melt coefficient (a_r), which can be calculated from site specific temperature, relative humidity and windspeed data on a daily basis, or the model can be calibrated to a single value that falls within the range of calculated values and represents the entire melt period. Surprisingly, the daily calculated melt coefficient provided little improvement over the seasonal value when used to predict daily melt. In fact in 2004, the seasonal melt coefficient provided a better model fit than the daily value. Since the hybrid model with a seasonal coefficient of melt performed as well or better than either the hybrid model with a daily melt coefficient or the energy budget model, it made sense to use the hybrid model with a seasonal melt coefficient when modeling snowmelt at the lysimeters. This approach also met one of the primary goals of the research, which was to find a simple model to predict melt under varying canopies using the least possible amount of site specific data.

Snowmelt modeling at the lysimeters

The hybrid model with the seasonal melt coefficient provided a reasonable fit to the observed daily melt at lysimeter 148, which is located in an opening between groups in the SG treatment. However the model consistently underpredicted melt at lysimeter 80, also located in an opening, where daily peak melt rates were often 30 to 50% higher than at lysimeter 148. The model performed better at the beginning of the melt season and towards the end of the snowmelt period. The underprediction of melt at lysimeter 80 in the middle of the season could be because the lysimeter was receiving additional melt from lateral flow, a problem common to many snowmelt lysimeters (Kattelmann, 2000). Presumably, in the early part of the melt season few ice layers were present in the snowpack, but as the melt season continued and many cycles of

freeze and thaw took place more lateral paths formed, so increasing the contribution area of the lysimeter (Kattelman, 2000). The problem disappeared later in the season because enough of the snowpack would have melted to eliminate the lateral flow paths.

Adjusting the radiation component of the hybrid model to account for the presence of the forest canopy considerably improved the model performance for lysimeter 65, which lies in one of the groups in the SG treatment and lysimeters 52 and 152 in the control. Forest canopies alter radiation by decreasing the shortwave radiation flux and increasing the longwave radiation flux with increasing canopy density. For low canopy densities solar radiation is at a maximum, while the longwave radiation flux is at a minimum (Dunne and Leopold, 1979). The opposite is true for high canopy densities. The lowest net radiation under the canopy, and hence the least amount of energy available for melt, occurs at intermediate canopy densities. At lysimeters 65, 52, and 152 the unadjusted model overpredicted melt because the radiation flux was too high. Within the range of canopy densities measured at these sites (60-70%) the net radiation under the canopy is lower than in the open, and the adjusted model did a good job of accounting for this effect on the radiation budget.

Although the adjusted hybrid model improved the fit between the observed and predicted values at lysimeters 65, 52 and 152, the Nash-Sutcliffe coefficients were still quite low. This could be due to several factors. First, temporary freezing of the drain hole or blockage of the drain hole by debris may have caused a lag between occurrence of melt and the time when it was recorded by the tipping bucket. Since the Nash-Sutcliffe coefficient is based on the fit between daily values, this would sharply reduce the strength of the correlation. Secondly, rainfall was subtracted from the total melt rates on a daily basis, but the rainfall totals were not adjusted for the effect of canopy interception. Rain gages at each lysimeter site would be needed to be able to correctly account for rainfall in the melt totals. Third, the melt predictions were based on daily average temperatures rather than on daily maximum temperatures so that melt rates on days with a high maximum temperature may have been underpredicted by the model. Finally, the equation used to calculate the net radiation under the canopy (equation 6) may not be a good predictor of the available energy in very dense lodgepole stands like those found at Tenderfoot. High stem densities in these stands may lead to a higher longwave flux than equation 6 predicts, so that the model underpredicts melt. Actual measurements of the radiation budget under the canopy and in different densities would be required to determine whether this is the case.

In contrast with lysimeters 65, 52 and 152, the best model fit at lysimeter 132 was obtained using a zero value for the canopy density. Lysimeter 132 is located within 5 m of the edge of the group, and is positioned on a southwest aspect. This location probably allows for additional energy input through the edge of the group, so increasing the melt rate. The fact that the model performed better towards the end of the melt season is consistent with this conclusion; as the season progressed the sun moved higher in the sky, so that the edge effect became less important. Once again, this highlights the difficulties inherent in modeling snowmelt in spatially complex stand structures with a lot of edges. In addition to the problems caused by shadows from adjacent trees in open areas, snowmelt rates for sites under the canopy but near the edge of stands may be higher than predicted because of the additional radiation flux.

Conclusions

Alternative silvicultural treatments such as thinning have been proposed as a means of increasing water yield and reducing wildfire hazard in forested watersheds in drought prone western North America, while also restoring the ecological structure and function of some forested areas. The results of this study demonstrate that manipulating tree spacing can have substantially different effects on snow accumulation and snowmelt depending on the spatial arrangement of the treatments. For central Montana, if forest harvest is to be conducted with the intent of increasing the water yield then the even thinning treatment maybe the most appropriate because of the significant increase in snow accumulation. However, the effect of group selection harvesting may vary depending on the orientation and size of openings.

Although the lysimeter data provided somewhat conflicting results, the thinning treatments did affect the rate of snowmelt. This could significantly change the timing and magnitude of snowmelt runoff, with a resultant impact on streamflow. If a slow release with a steep climbing limb and steady consistent recession limb were desired the appropriate treatment would be the group retention unit. The open sites in the group unit may yield larger amounts on a daily basis, but the retention groups would give a slower consistent melt on a daily basis thus prolonging melt. Alternatively, the evenly thinned unit could result in a faster flashier hydrograph due the sparse canopy and high accumulations. Further research on a watershed scale would be needed to determine if this is the case.

Modeling the melt under various degrees of forest canopy coverage is best accomplished using a hybrid temperature index model with the radiation component adjusted for canopy. However, the ability of such models to predict melt in thinned stands is limited by high spatial variability in the radiation flux, due to shading in clearings and additional radiation inputs near forest edges.

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Table 1. Area, mean aspect, minimum, maximum and mean elevation, and mean slope of the even and group retention shelterwood-with-reserve treatments and the control.

Treatment	Area (ha)	Mean aspect (degrees)	Elevation (m)			Mean Slope (%)
			Min.	Max.	Mean	
Even thinning – east aspect	32	75	2,191	2,259	2,229	9
Even thinning – west aspect	12	297	2,198	2,260	2,230	11
Group retention thinning – east aspect	25	64	2,168	2,234	2,200	12
Group retention thinning – west aspect	32	290	2,176	2,261	2,221	13
Control	13	216	2,175	2,265	2,237	9

Table 2. Snow water equivalent (cm) at the Onion Park SNOTEL site and in the treatments and the control at the time of sampling in 2003, 2004 and 2005. Values for the treatments and control are the mean of all sample locations, along with the standard deviation, coefficient of variation (CV), minimum and maximum values and number of samples (N).

	2003			2004			2005			Average		
Onion Park	34.0			34.8			29.2			32.7		
Treatment	SE	SG	Control	SE	SG	Control	SE	SG	Control	SE	SG	Control
Mean	27.6	21.3	20.4	33.6	27.0	28.0	20.1	17.8	18.4	27.1	22.0	22.3
Std Dev	3.1	7.1	3.5	3.9	6.3	4.7	3.0	5.4	2.9	3.3	6.3	3.7
CV (%)	11	33	17	12	23	17	15	30	16	13	29	17
Min	19.5	3.8	12.7	15.2	5.1	18.6	11	5.9	11	15.2	4.9	14.1
Max	36.0	34.7	27.9	43.2	41.5	47.4	27.9	30.5	23.7	35.7	35.6	33.0
N	102	123	45	102	144	40	99	142	40	101	136	42

Table 3. Observed and model predicted values for the mean snow water equivalents (cm) in the control and the SE treatment in 2003, 2004 and 2005. D_v is the average percent deviation from the observed values.

Year	Control			SE Treatment		
	Observed	Predicted	Difference	Observed	Predicted	Difference
2003	20.4	23.9	+3.5	27.6	27.6	0
2004	28.0	25.5	-2.5	33.6	28.6	-5.0
2005	18.4	18.1	-0.3	20.1	21.2	+1.1
D_v	9.4%			7.5%		

Table 4. Timing of beginning and end of snowmelt at Onion Park (OP) and the snowmelt lysimeters in 2004. SG-I and SG-O indicate sites inside and outside of the retention groups in the SG treatment, respectively. SE indicates the even thinning treatment.

<i>Site #</i>	<i>Start of Melt</i>	<i>End of</i> <i>Melt</i>	<i>Aspect</i>	<i>Elevation</i> <i>(m)</i>	<i>% Open</i>	<i>SWE</i>	<i>Location</i>
<i>OP</i>	<i>19-Mar</i>	<i>04-Jun</i>			<i>100</i>		<i>Open</i>
132	22-Apr	11-Jun	SW	2262	0.37	25.4	SG-I
148	09-Apr	7-Jun	SW	2256	1.00	23.3	SG-O
65	09-Apr	11-Jun	NW	2243	0.32	35.6	SG-I
80	09-Apr	11-Jun	W	2243	0.99	33.8	SG-O
108	05-May	11-Jun	W	2208	0.96	35.6	SG-O
152	09-Apr	08-May	Flat	2274	0.36	26.7	Control
52	24-Apr	11-Jun	NW	2246	0.26	30.5	Control
239	07-May	11-Jun	NW	2196	0.93	34.8	SE

Table 5. Nash Sutcliffe coefficient of efficiency (R_{NS}^2) for temperature index (TI), hybrid and energy balance (EB) snowmelt models when used to predict snowmelt at Onion Park SNOTEL station in 2004 and 2005.

<i>Model</i>	<i>2004</i>	<i>2005</i>
<i>TI</i>	0.67	0.43
<i>Hybrid Calculated</i>	0.25	0.23
<i>Hybrid Published</i>	0.10	0.29
<i>EB</i>	0.10	0.25

Table 6. Nash Sutcliffe coefficient of efficiency R_{NS}^2 for hybrid and canopy adjusted hybrid snowmelt models when used to predict melt at six lysimeter sites in 2004. Lysimeters 148 and 80 are in open areas, so the hybrid model and the hybrid canopy model used the same parameter sets.

	<i>Hybrid</i>	<i>Hybrid Canopy</i>
<i>52</i>	-1.91	0.34
<i>152</i>	0.29	0.71
<i>65</i>	-2.61	0.40
<i>132</i>	-1.46	0.22
<i>148</i>	0.29	NA
<i>80</i>	0.43	NA

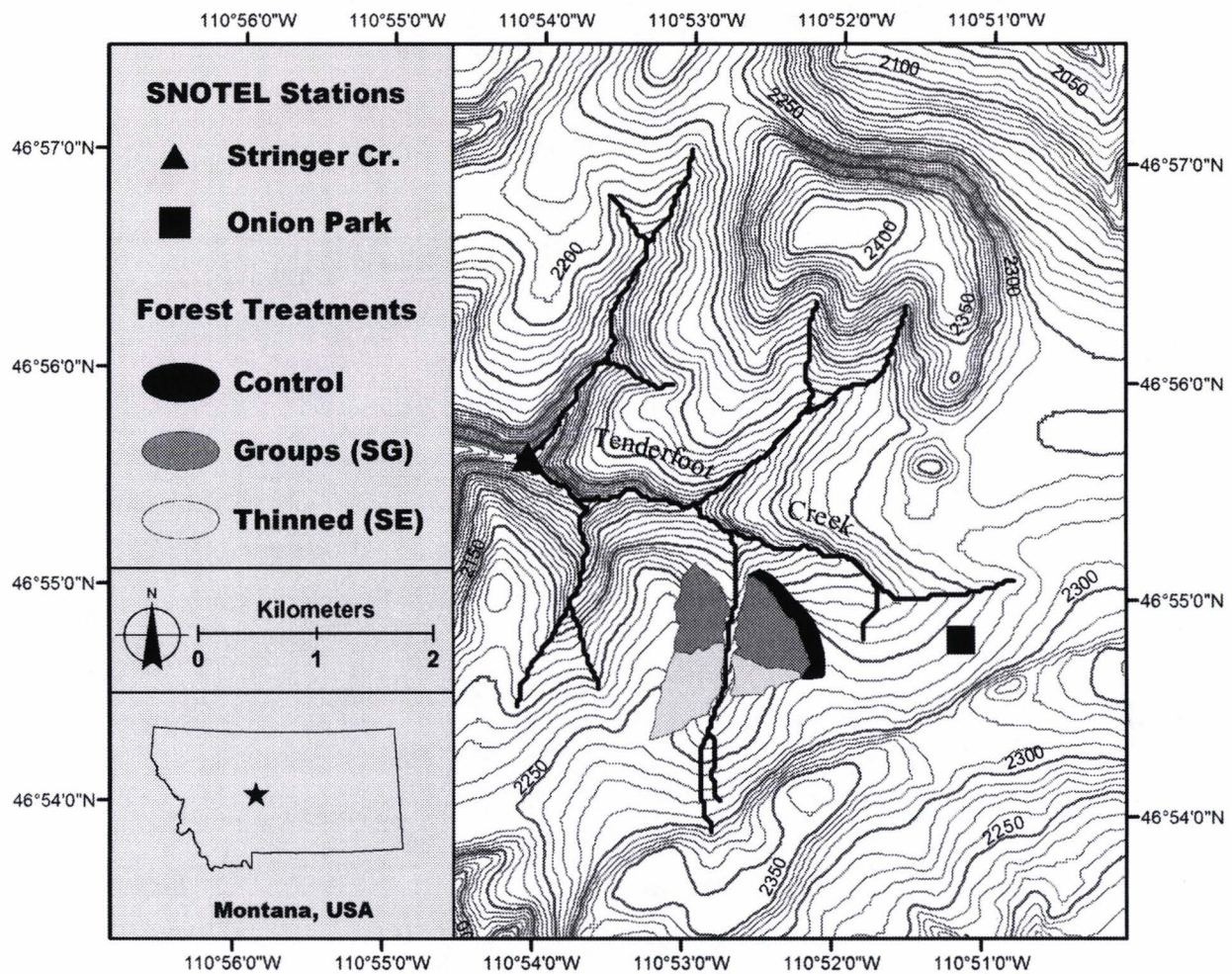


Figure 1. Location of study sites at Tenderfoot Creek Experimental Forest in west-central Montana. Main map shows location of treatments in the Sun Creek subwatershed, and the Onion Park and Stringer Creek SNOTEL stations. Contour interval is 10 m.



Figure 2. Even thinning treatment in the Sun Creek watershed, April 2003



Figure 3. Group retention thinning treatment in the Sun Creek watershed. April 2003. Foreground is an opening between groups. Open corridors in the distance are part of the group retention treatment on the opposite hill slope.

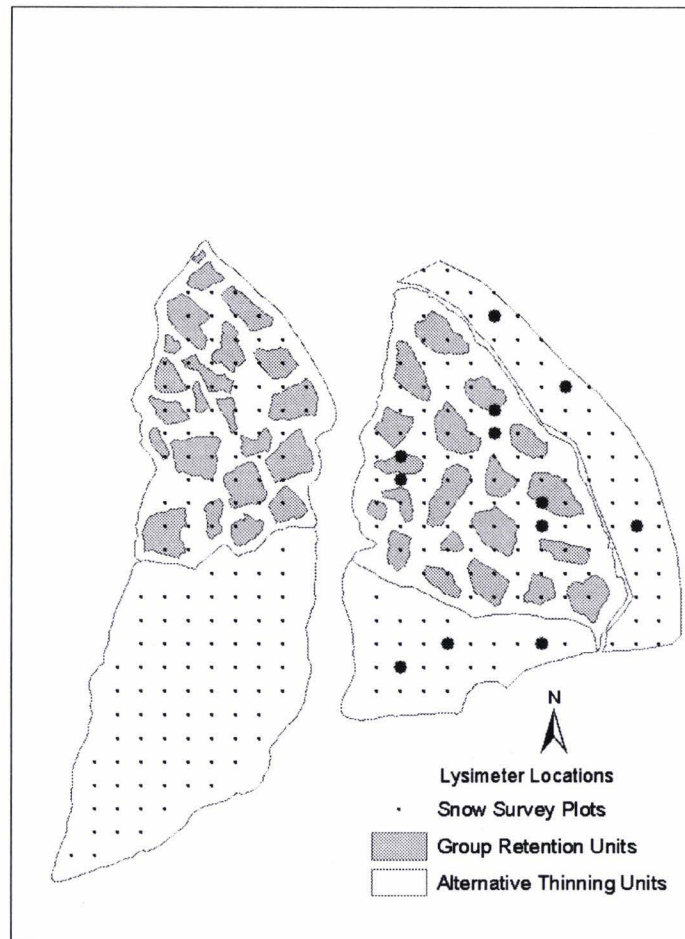


Figure 4. Location of the twelve lysimeters (shaded circles) in the two treatments and in the control.

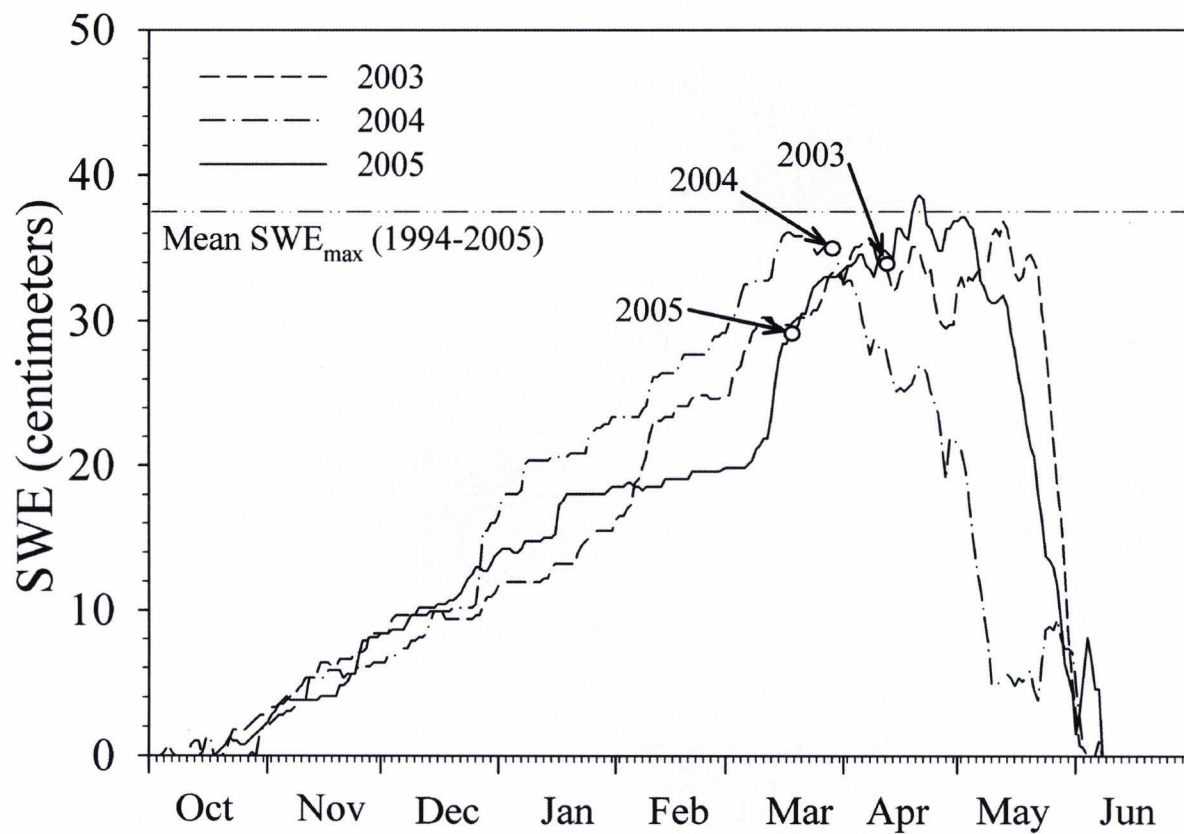


Figure 5. Snow water equivalent (SWE) at the Onion Park SNOTEL site in 2003, 2004 and 2005. Labeled circles indicate the start of each 3-day measurement period in each year.

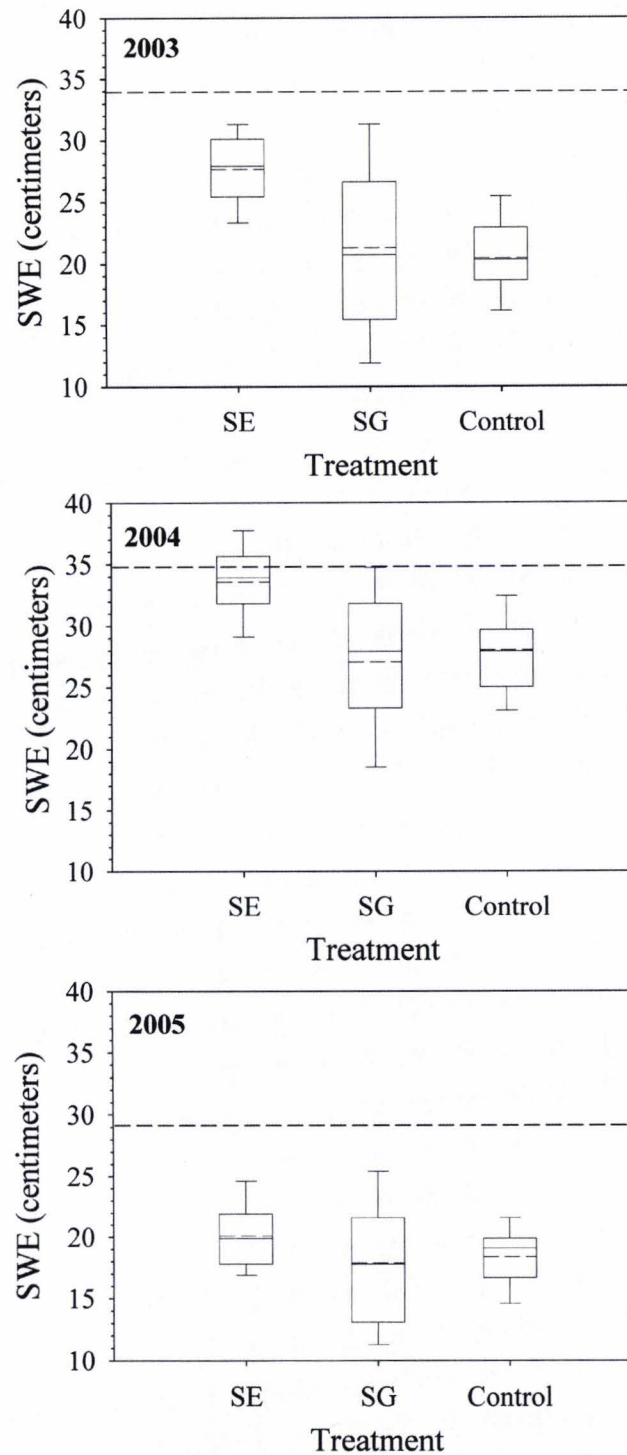


Figure 6. Snow water equivalent (SWE) in even (SE) and group retention (SG) shelterwood-with-reserve treatments and control in 2003, 2004 and 2005. Solid and dashed lines in boxes indicate median and mean, respectively. Box ends indicate 25th and 75th percentiles. Whiskers indicate 10th and 90th percentiles. Horizontal dashed lines indicate the SWE at the Onion Park SNOTEL site at the start of the sampling period.

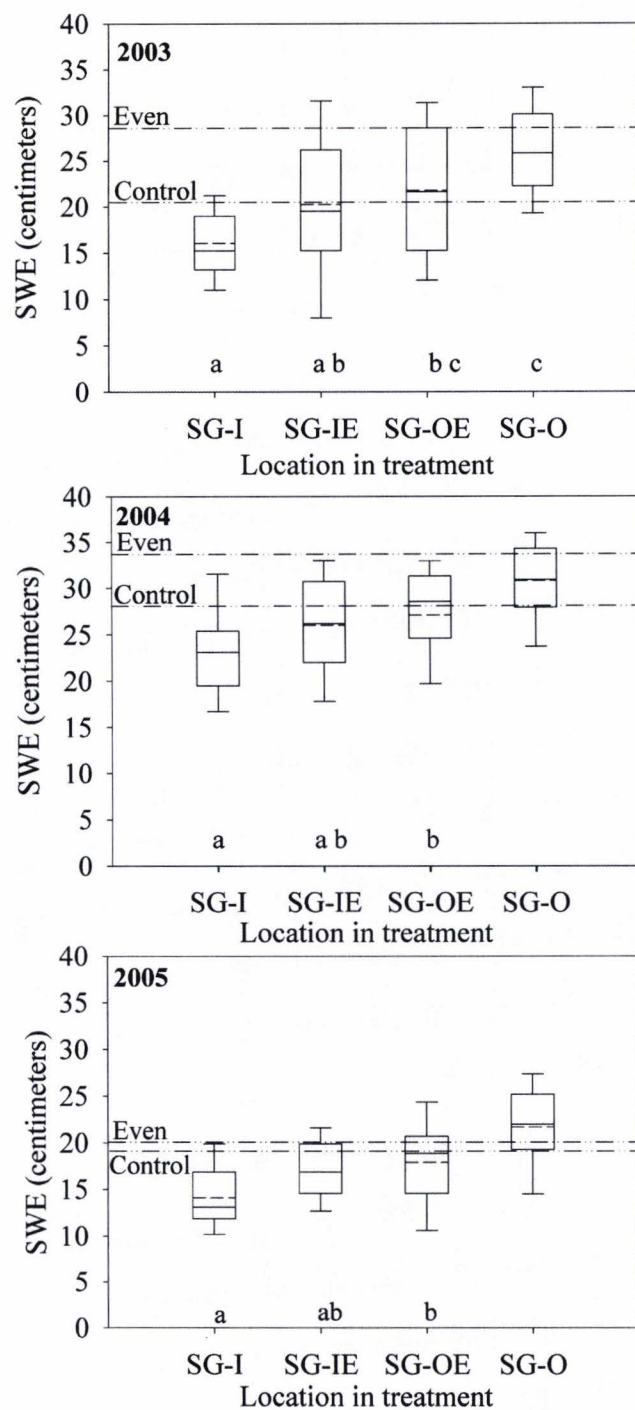


Figure 7. Snow water equivalent in shelterwood-with-reserve group treatment inside groups (SG-I), at inside edge of groups (SG-IE), at outside edge of groups (SG-OE) and outside groups (SG-O) in 2003, 2004 and 2005. Solid and dashed lines in boxes indicate median and mean, respectively. Box ends indicate 25th and 75th percentiles. Whiskers indicate 10th and 90th percentiles. Dot-dot-dash lines indicate mean SWE in even thinning treatment and control. Treatments with same letter (a, b etc.) have means that are not significantly different at $P = 0.05$.

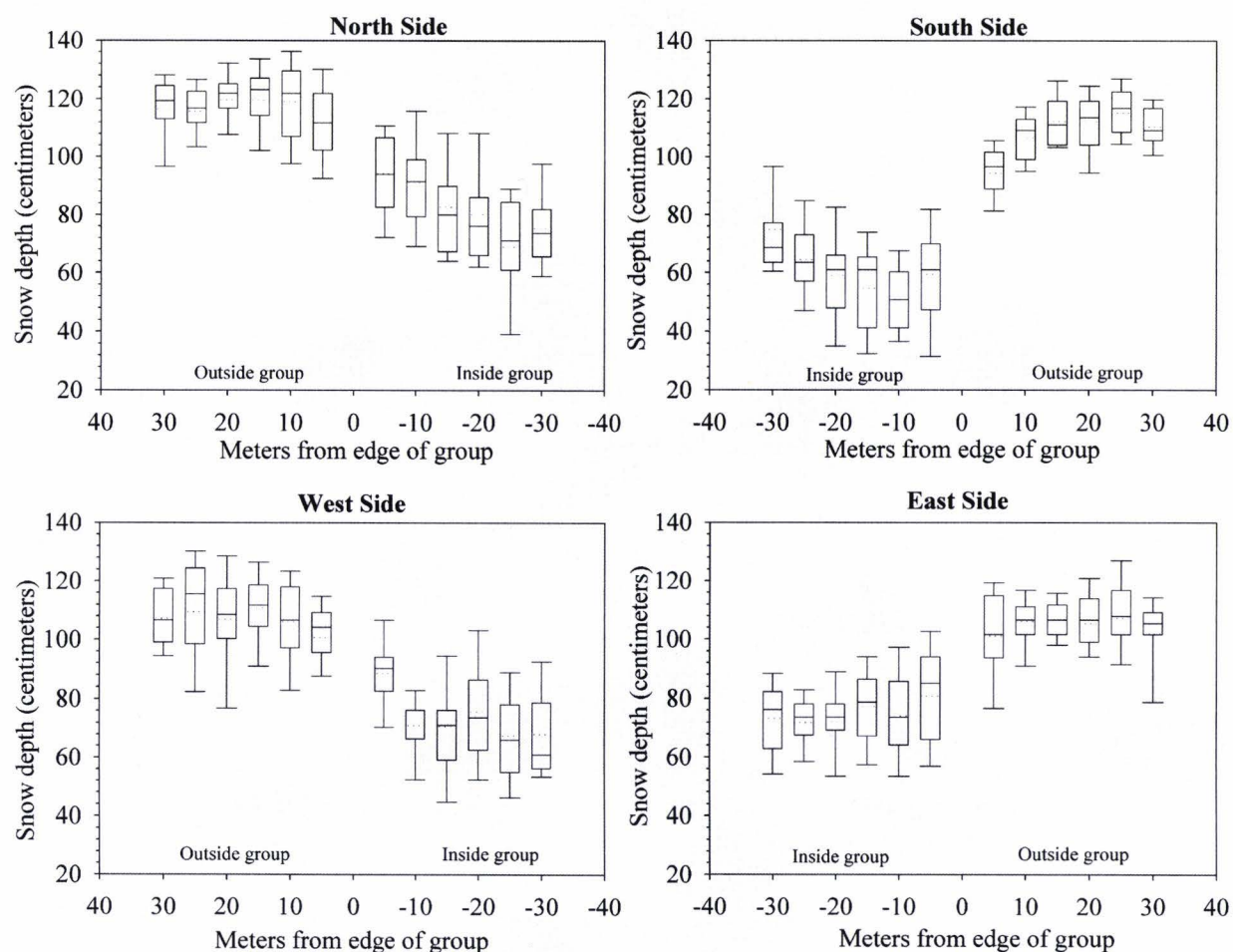


Figure 8. Snow depth along transects on north, south, west and east sides of 19 retention groups in 2005. Solid and dashed lines in boxes indicate median and mean, respectively. Box ends indicate 25th and 75th percentiles. Whiskers indicate 10th and 90th percentiles.

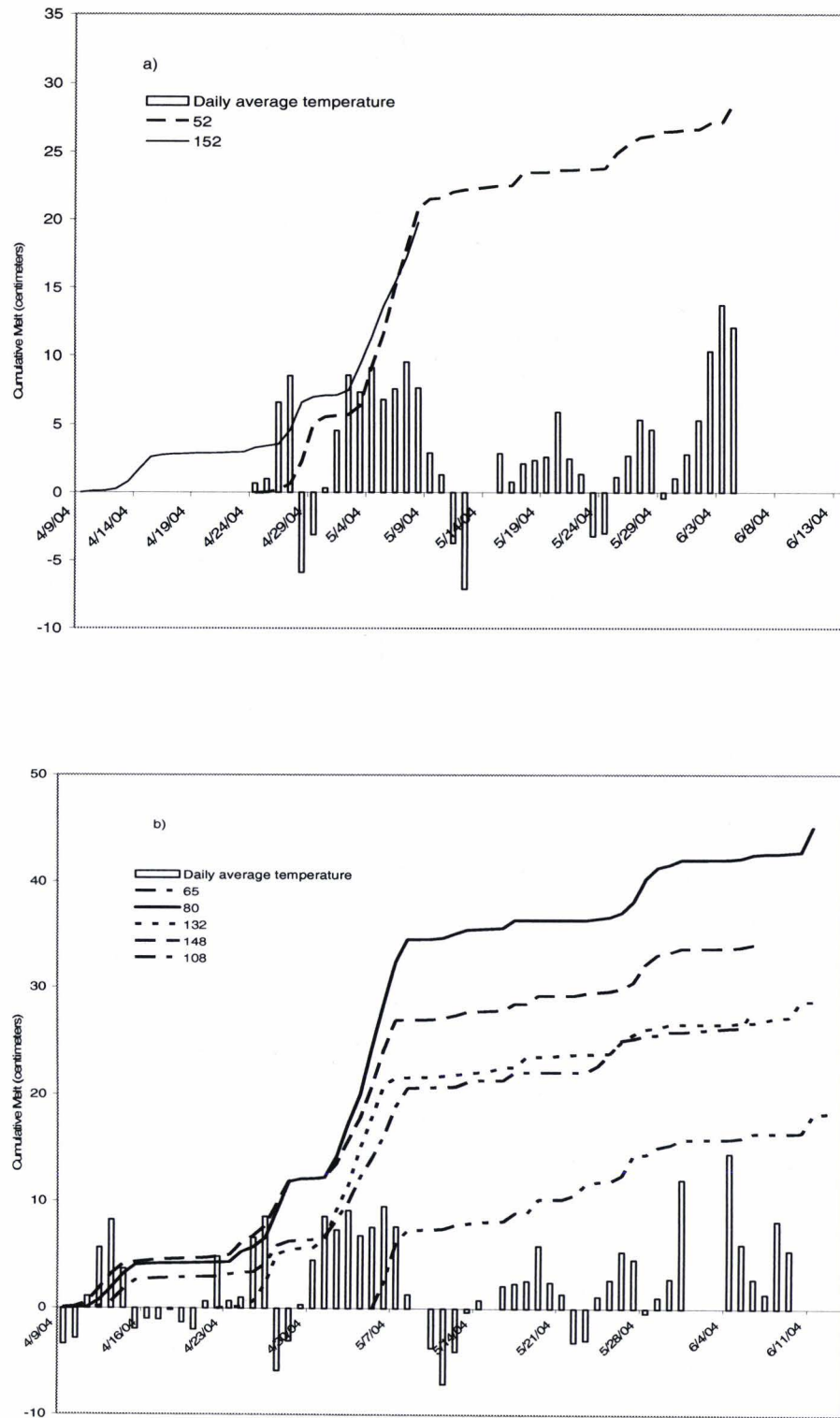


Figure 9. Cumulative melt rates in snowmelt lysimeters 2004 a) in the group retention unit and b) control sites 80, 148 and 108 are open sites, while sites 65 and 132 are group sites. Site 108 experienced technical problems during the melt season.

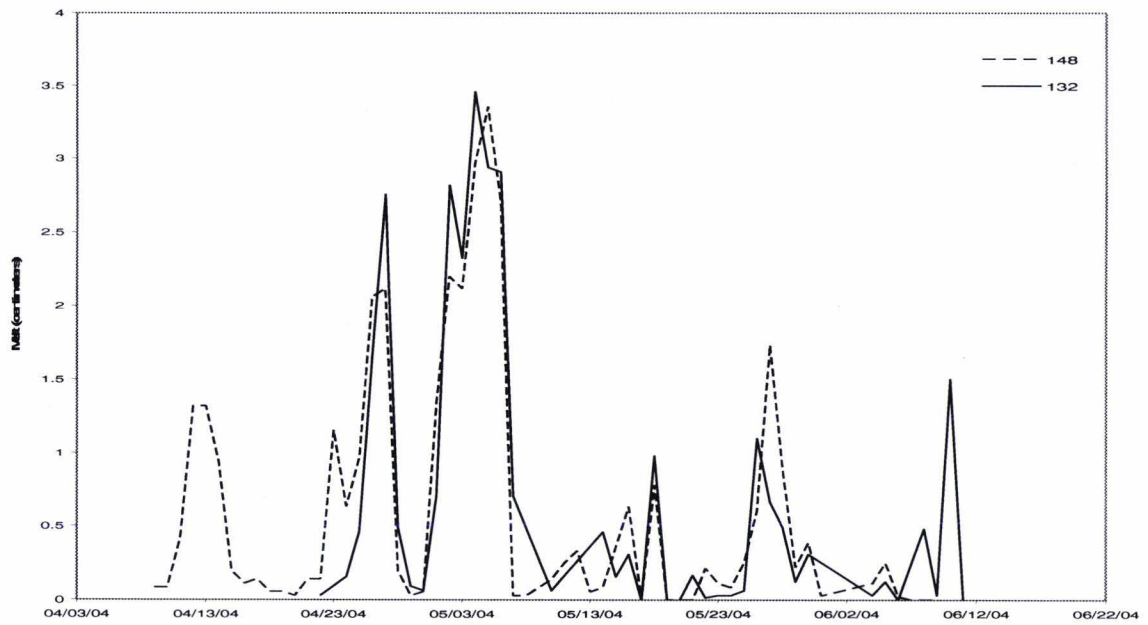
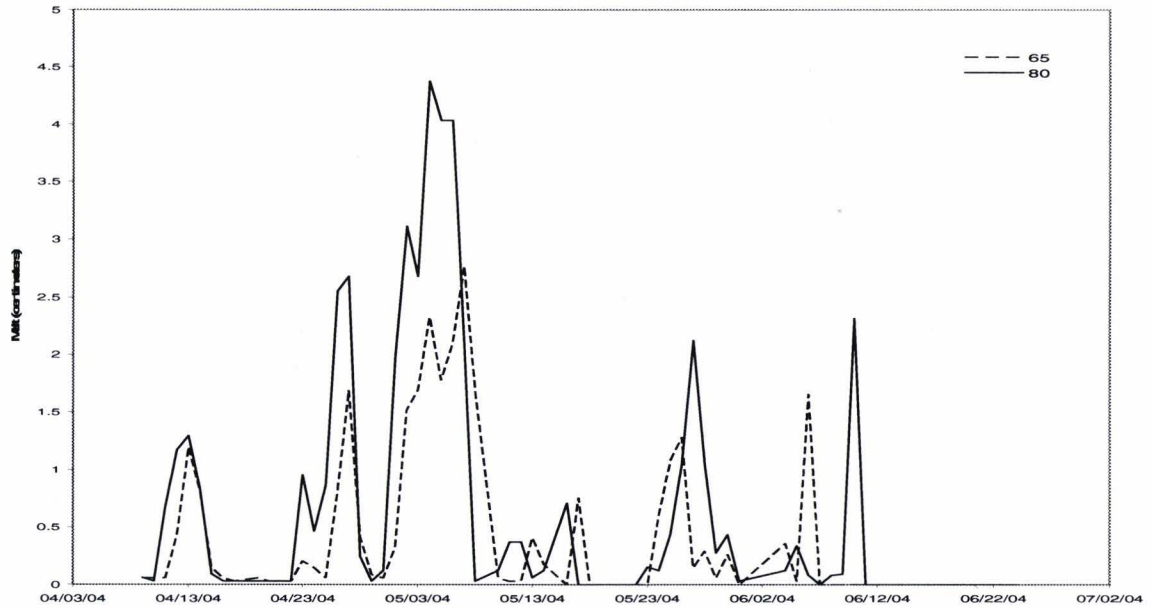


Figure 10. A comparison of daily melt for paired lysimeters 2004. Lysimeter 80 and 148 are open sites while 65 and 132 are located inside the retention groups.

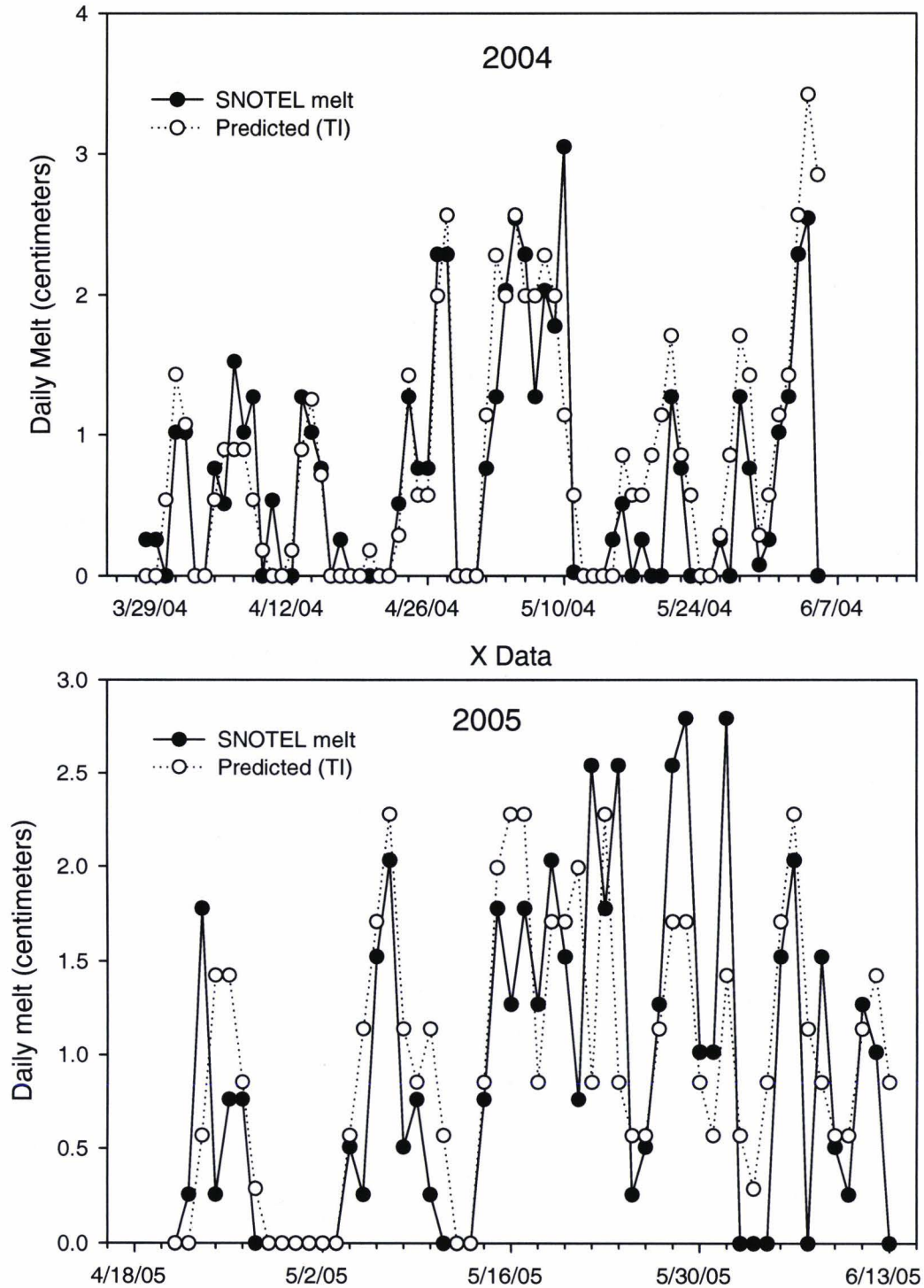


Figure 11. Daily melt at Onion Park and daily melt predicted by the temperature index model, 2004-2005.

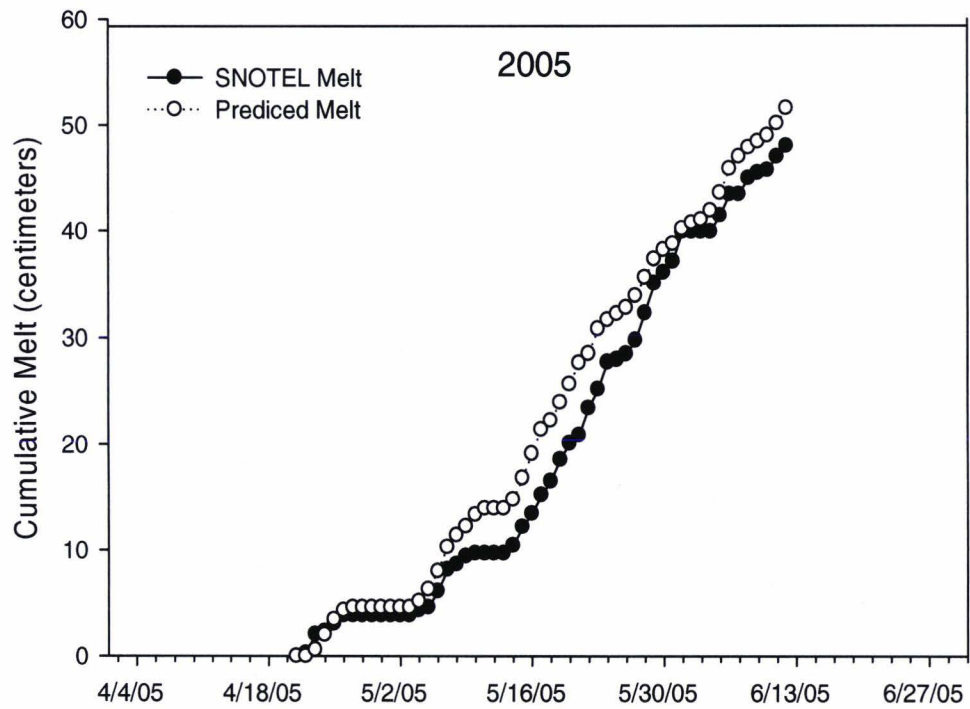
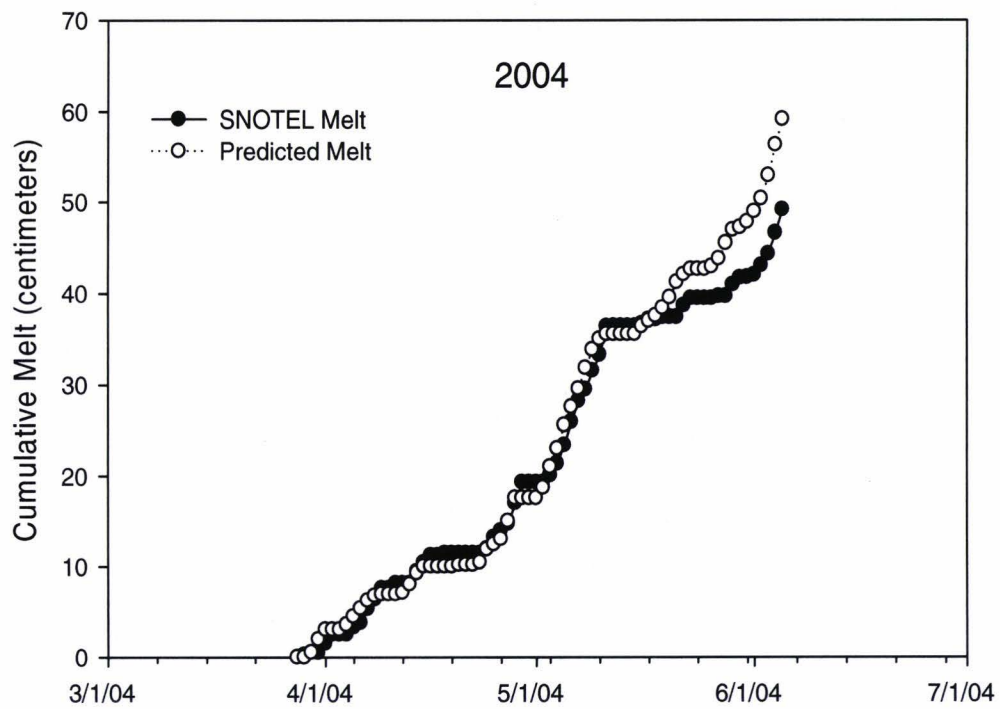


Figure 12. Cumulative melt at Onion Park in 2004 and 2005 compared to the melt predicted by the temperature index model.

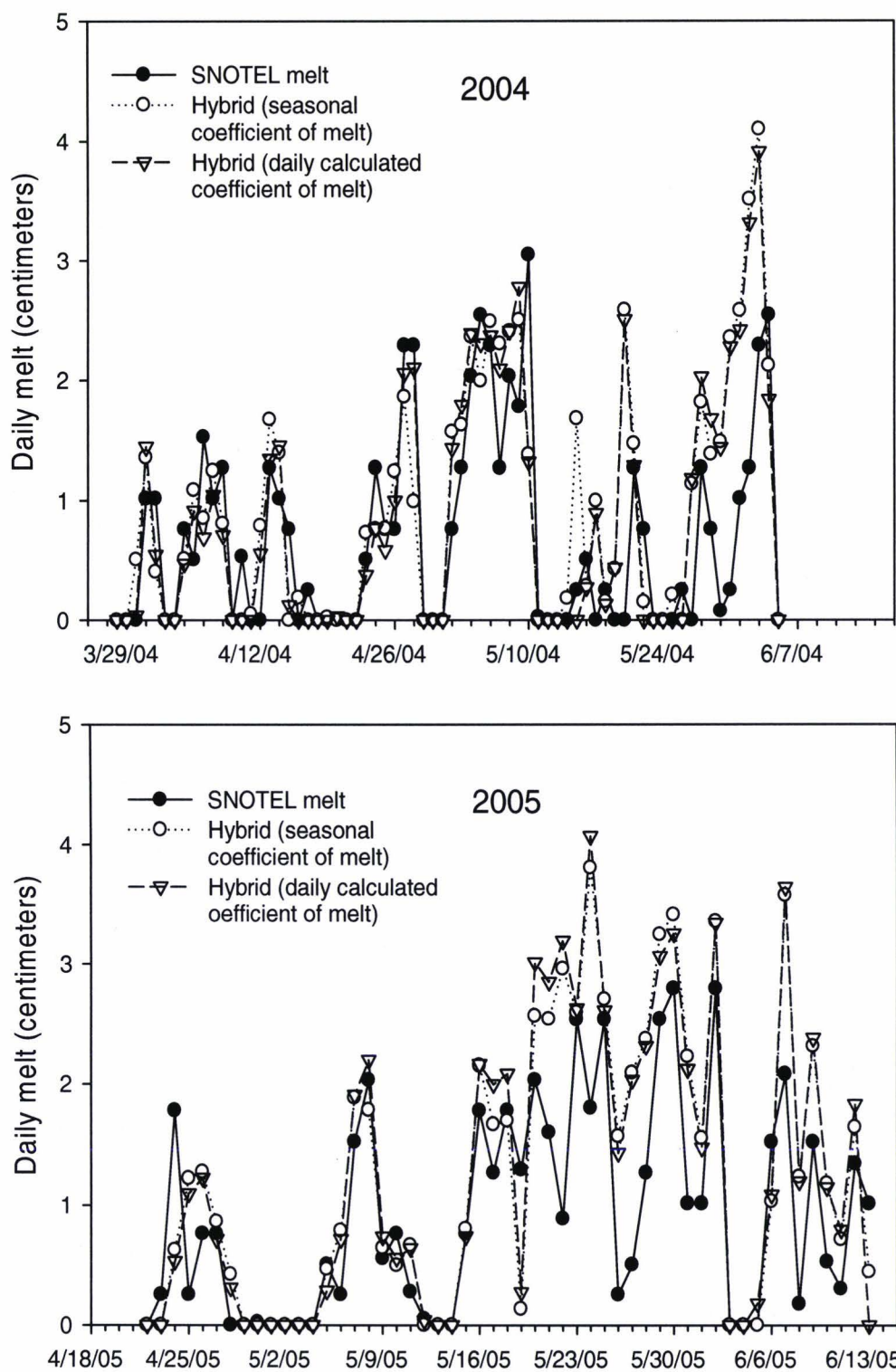


Figure 13. Observed daily melt at Onion Park compared to the melt predicted by the hybrid model in 2005.

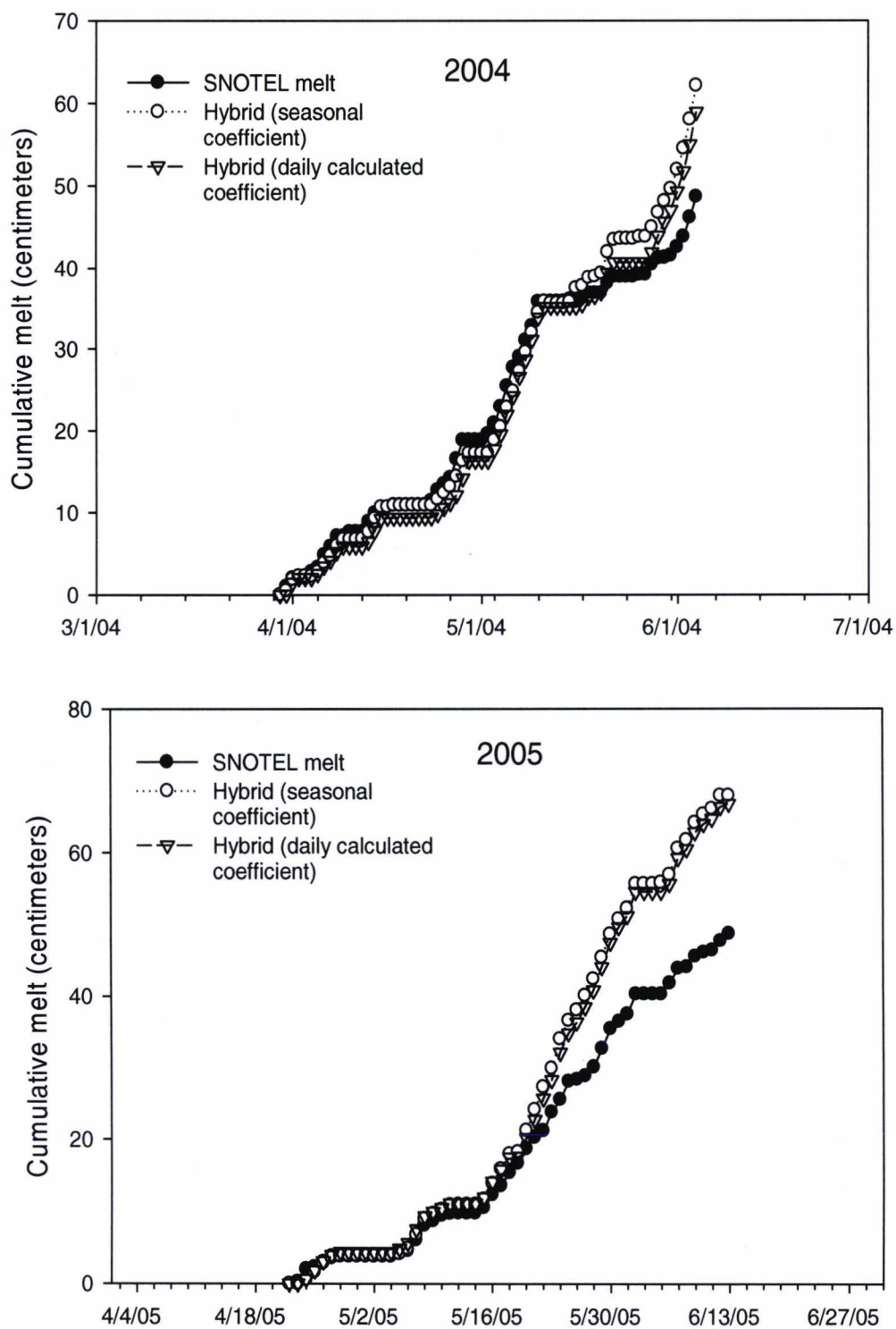


Figure 14. Observed cumulative snowmelt at Onion Park compared to the snowmelt predicted using the hybrid model with daily melt coefficient.

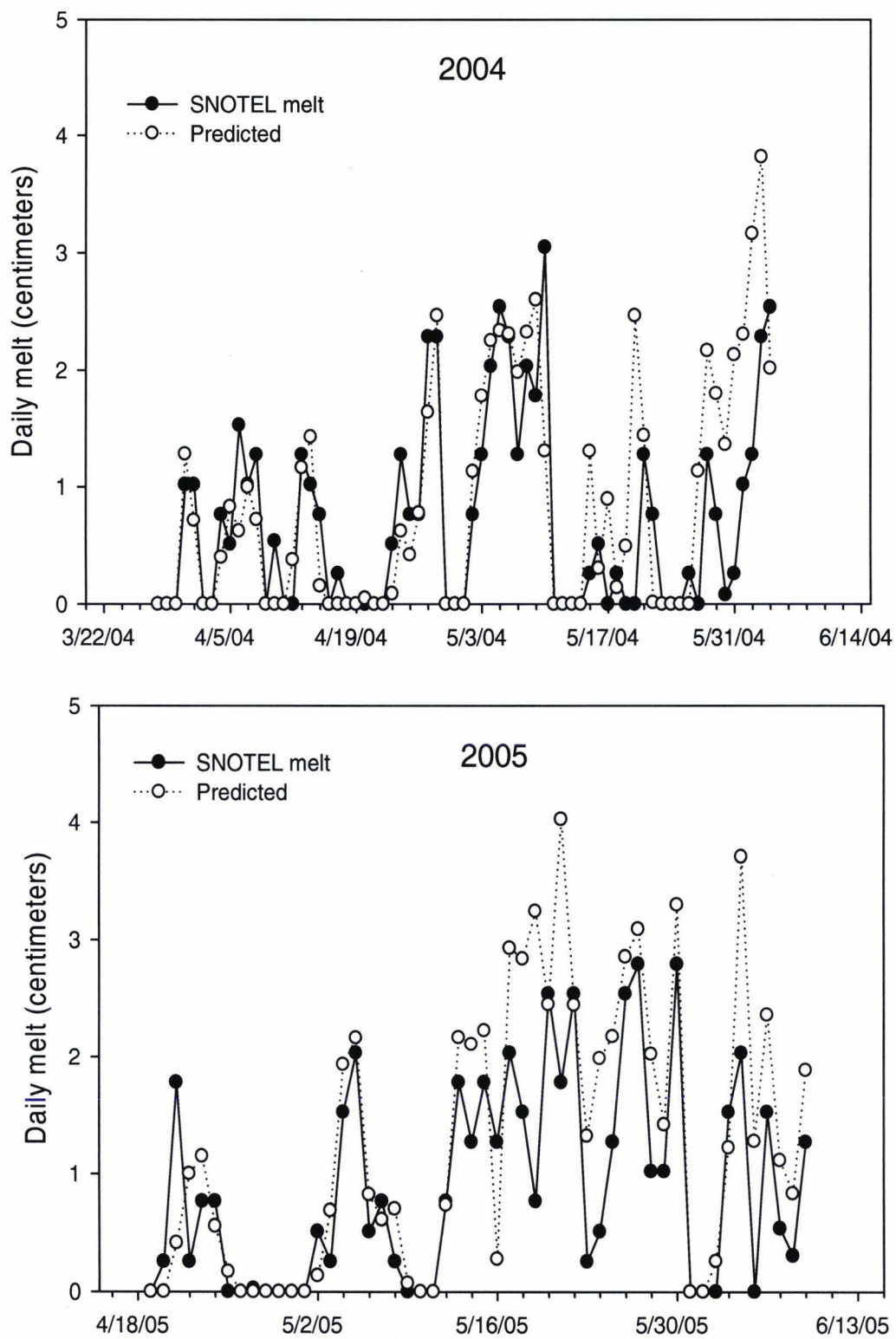


Figure 15. Observed daily melt at Onion Park compared to the predicted daily melt obtained using the energy balance model.

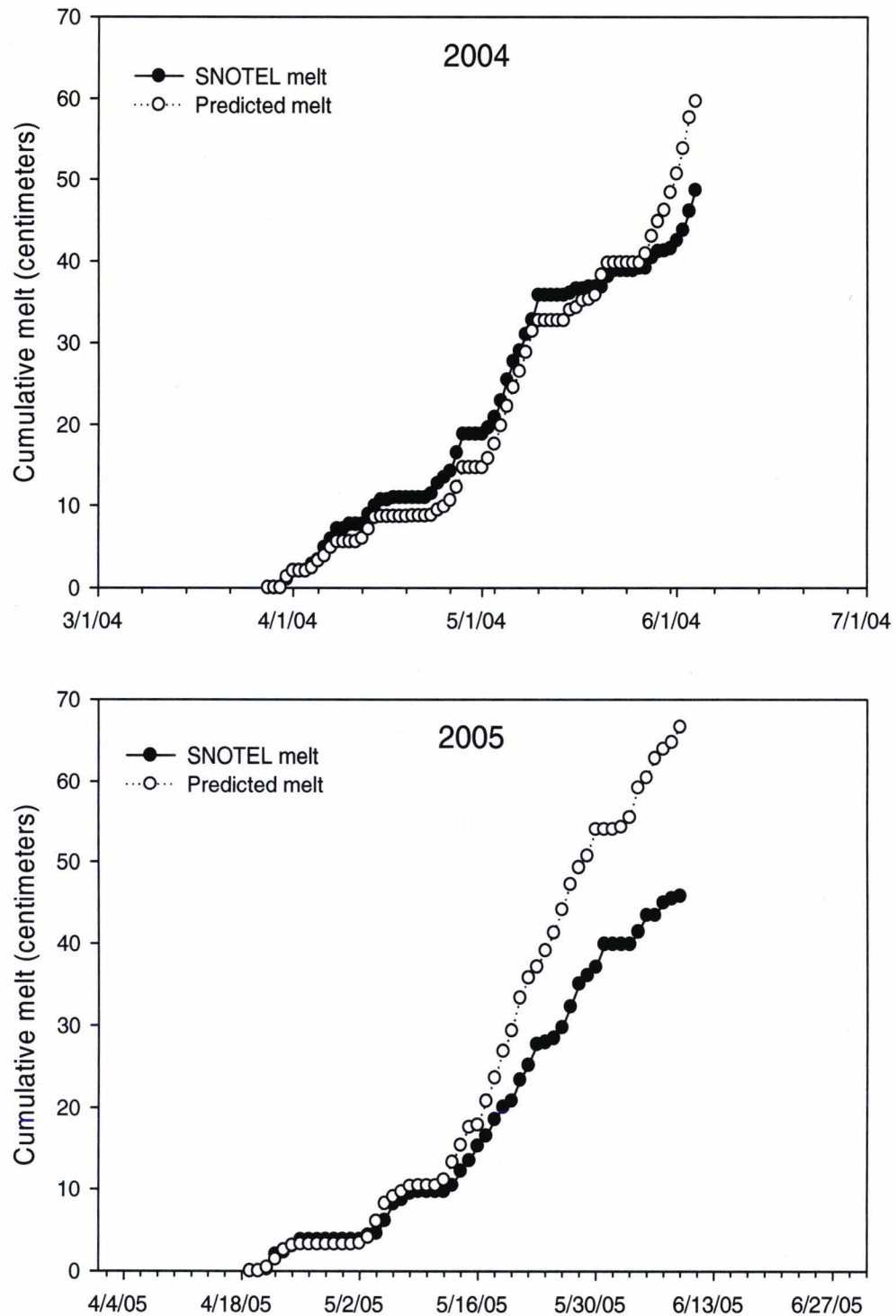


Figure 16. Observed cumulative melt at Onion Park compared to cumulative melt predicted by the energy balance model in 2004 and 2005.

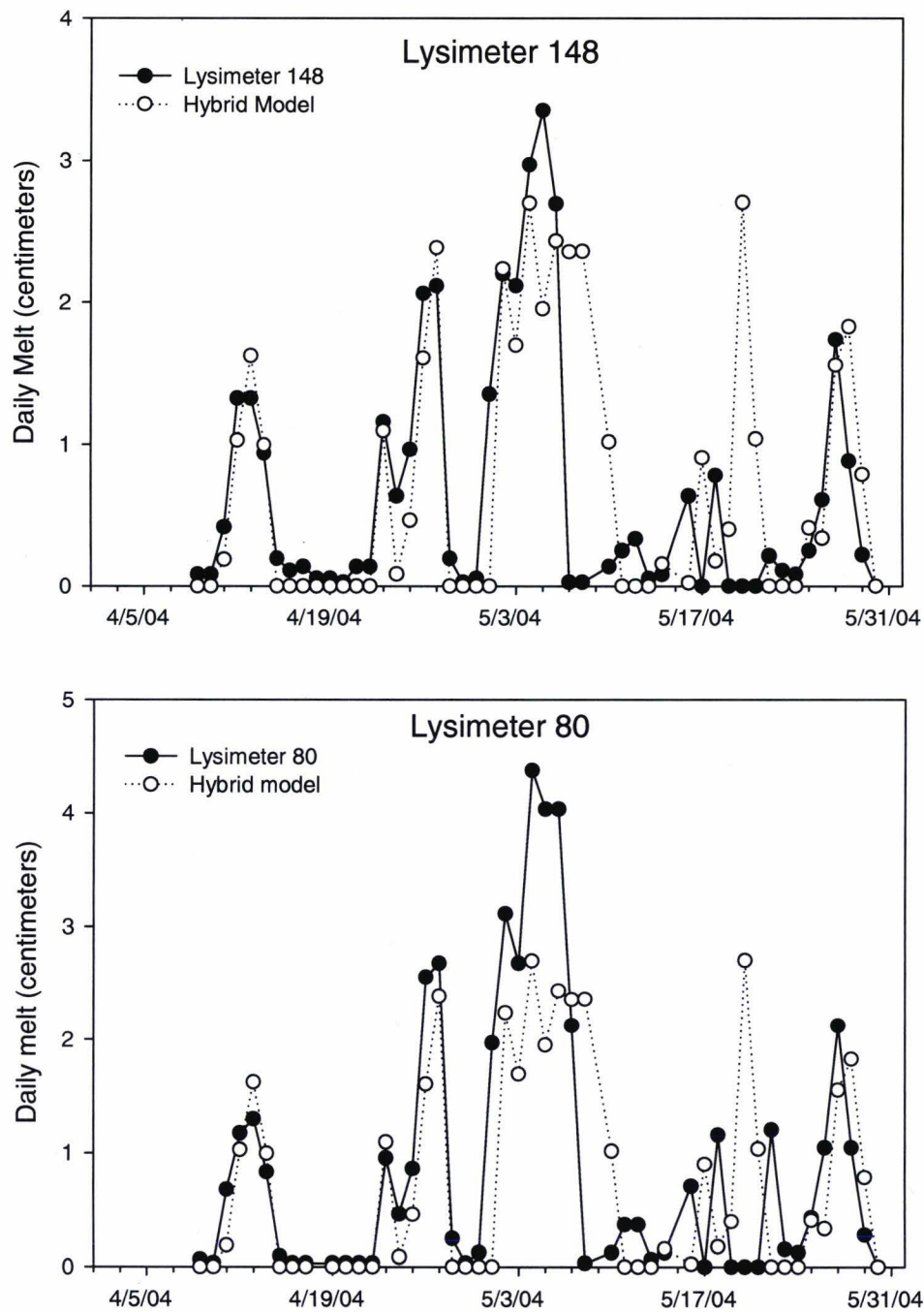


Figure 17. Daily melt at the open site lysimeters in 2004 compared to the melt predicted by the hybrid model.